Space Weather in the Upper Atmosphere
and
Current Data Assimilation at SEC and possible use of COSMIC

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CIRES, University of Colorado and
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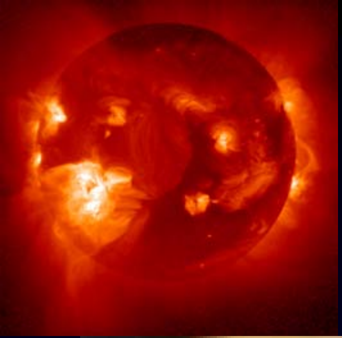
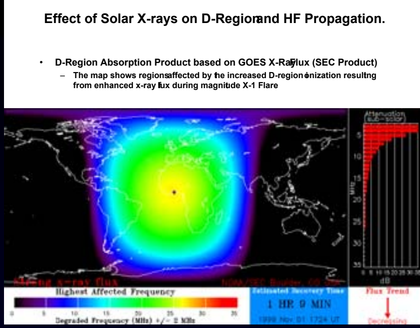
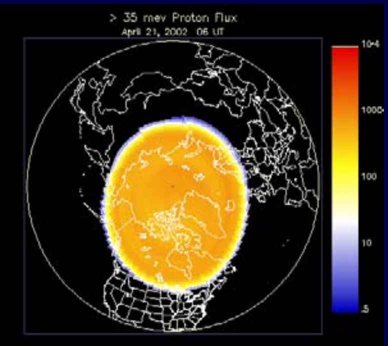
JCSDA Seminar, Camp Springs

August 16th, 2006



Space Environment Center
National Weather Service
Boulder, Colorado

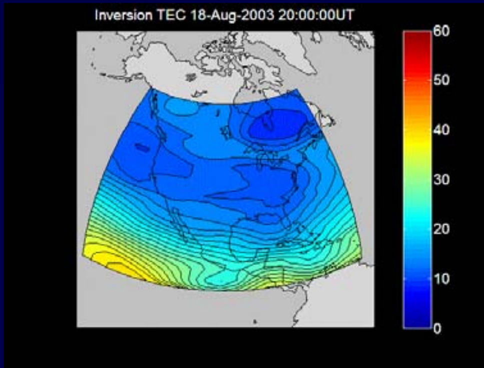




Forecast and Analysis Branch

24/7 Space Weather Operational Center

The nations official provider of real-time alerts, warnings, and products



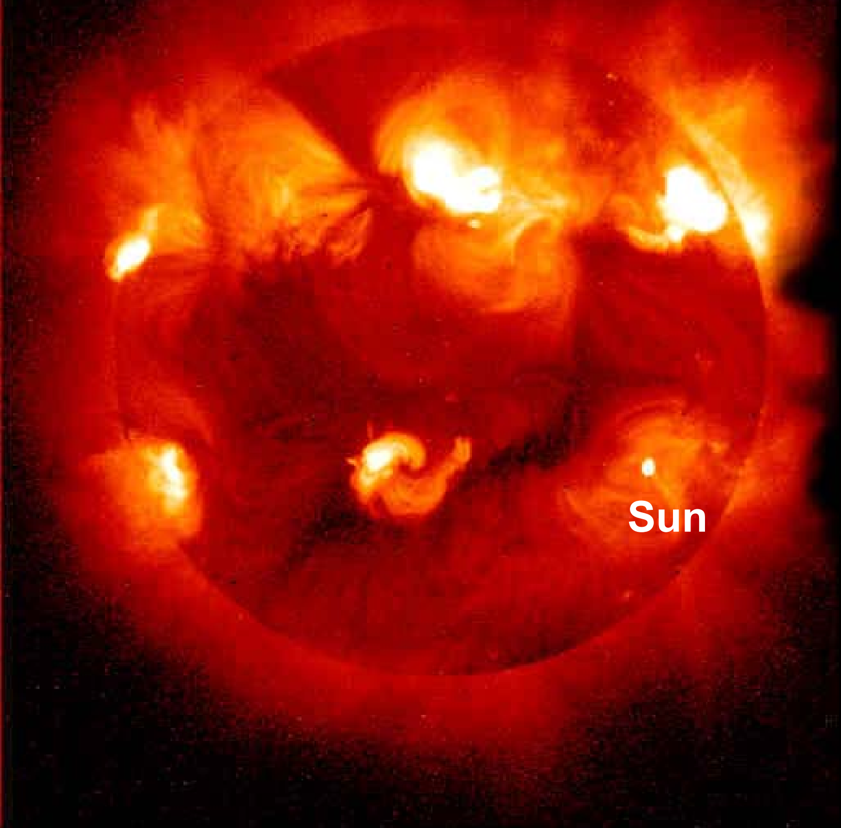
Overview

- What is space weather?
- What is the impact and who are the users?
- Understanding the sources of variability in the upper atmosphere
- US-TEC: an ionospheric product for navigation
- Future use of COSMIC

Space Weather:

What is it?

Space Weather refers to changes in the space environment near Earth

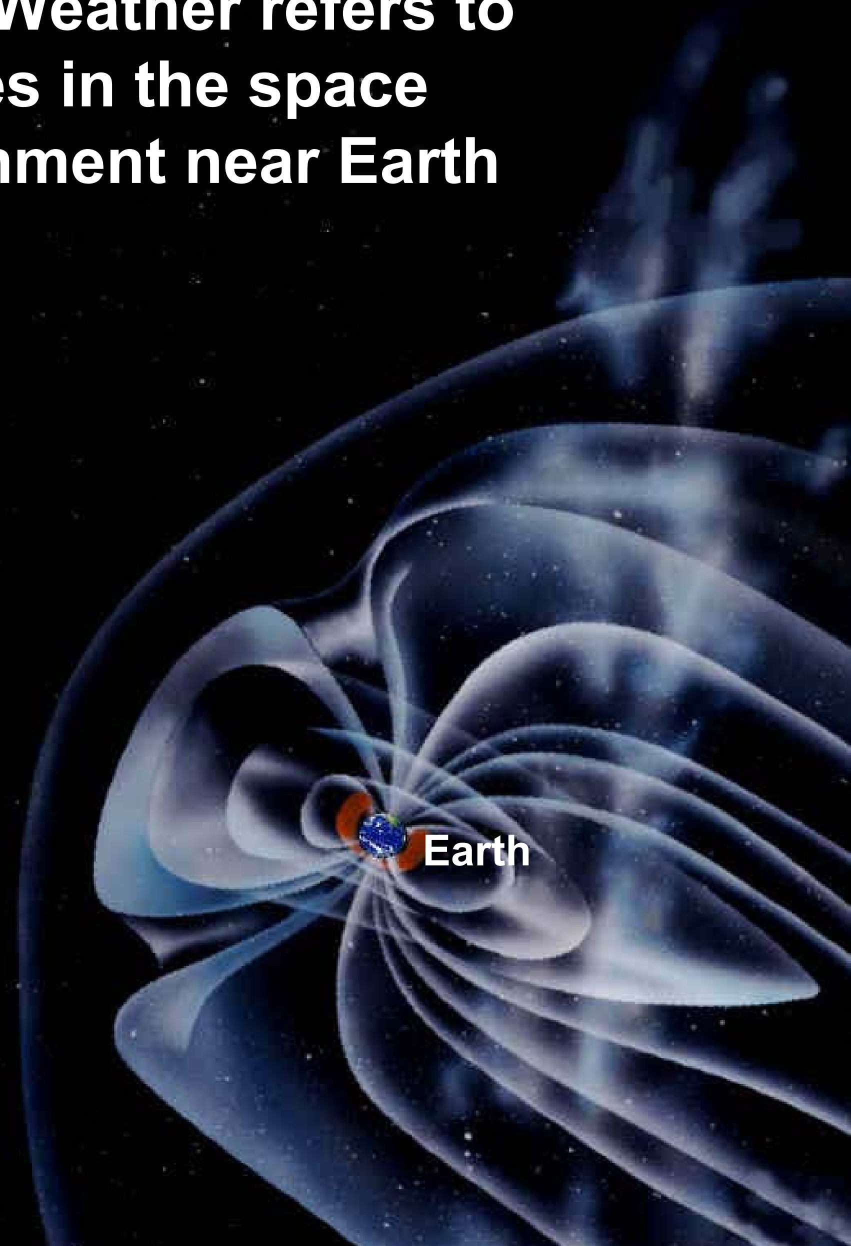


Solar energy released in the form of…
- **Light**
- **Particles (electrons and protons)**
- **Magnetic Field**

Activity Cycles
- **e.g. 11 years**

Lower atmosphere
- **Wave forcing from below**

Internal variability



SEC: http://www.sec.noaa.gov

- Space Weather Storms come in three categories
- Each category arrives at a different speed
- Each category affects different users and technologies

	Bursts of X-ray and EUV radiation	Energetic Particles (electrons and protons)	CMEs that produce Geomagnetic Storms
Arrival Time	8 minutes	30 min. to 16 hrs.	1 to 4 days
Systems Affected	Radio Comm. VLF Navigation Airlines	Satellites Astronauts Airlines	Power Companies Radio Comm. Airlines GPS Navigation

Space Weather = Eruptions

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Movie Courtesy of NASA


NOAA Space Weather Scales

Geomagnetic Storms

G 5

G 4

G 3

G 2

G 1

Solar Radiation Storms

S 5

S 4

S 3

S 2

S 1

Radio Blackouts

R 5

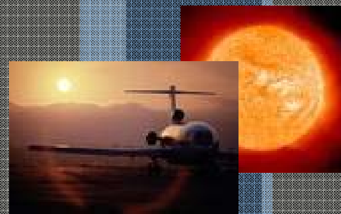
R 4

R 3

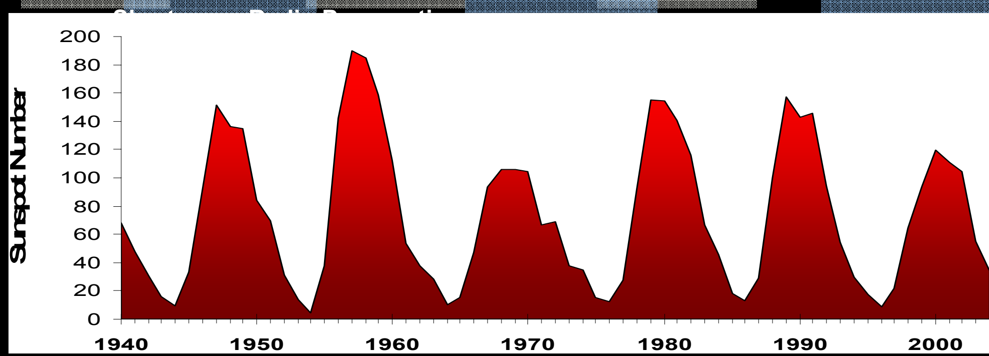
R 2

R 1

Growth of Space Weather Customers



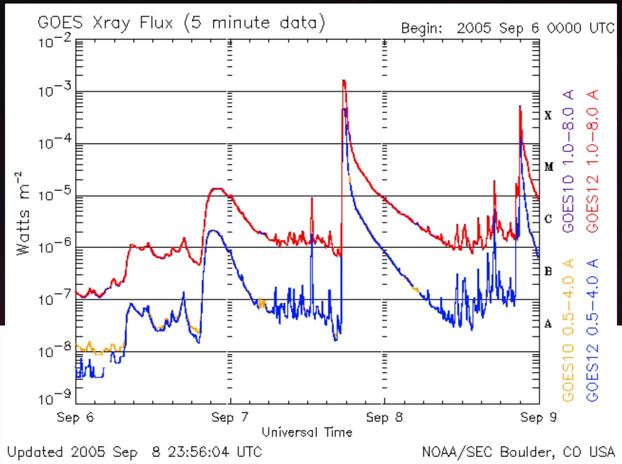
Commercial Space Transportation
Airline Polar Flights
Microchip technology
Precision Guided Munitions
Cell phones
Atomic Clock
Satellite Operations
Carbon Dating experiments
GPS Navigation
Ozone Measurements
Aircraft Radiation Hazard
Commercial TV Relays
Communications Satellite Orientation
Spacecraft Charging
Satellite Reconnaissance & Remote Sensing Instrument Damage
Geophysical Exploration.
Pipeline Operations
Anti-Submarine Detection
Satellite Power Arrays
Power Distribution
Long-Range Telephone Systems
Radiation Hazards to Astronauts
Interplanetary Satellite experiments
VLF Navigation Systems (OMEGA, LORAN)
Over the Horizon Radar
Solar-Terres. Research & Applic. Satellites
Research & Operations Requirements
Satellite Orbit Prediction
Solar Balloon & Rocket experiments
Ionospheric Rocket experiments
Radar

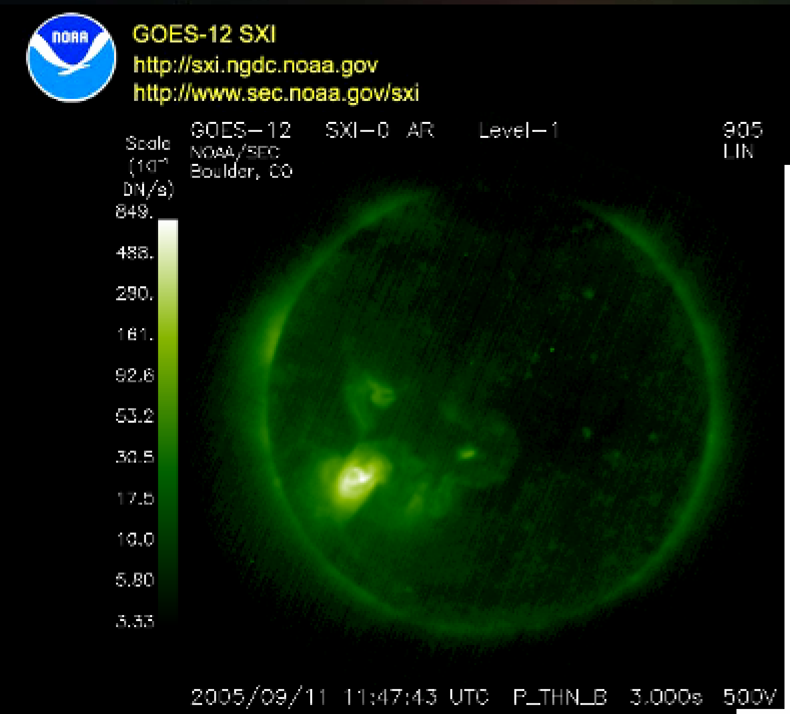


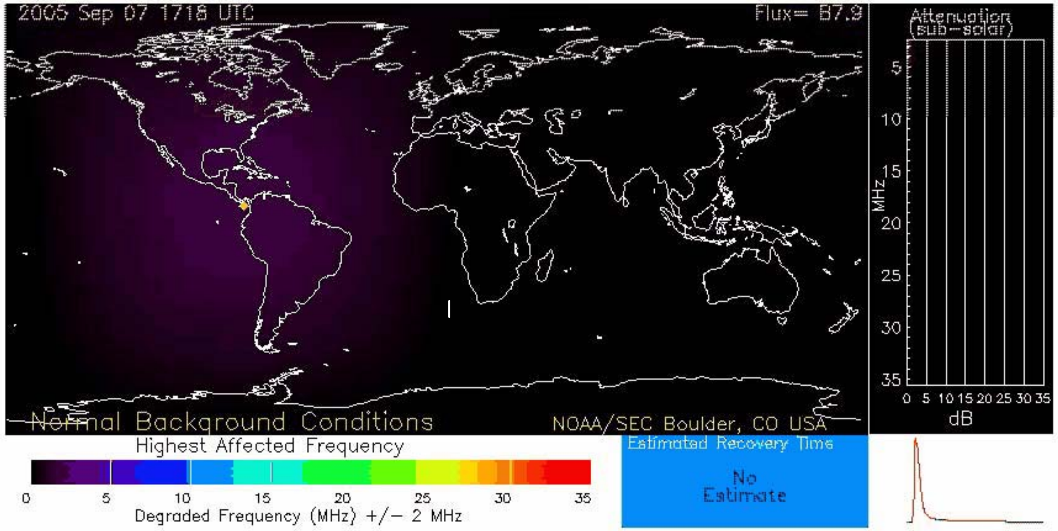
Sunspot Cycles

Airlines

GOES XRS







GOES SXI

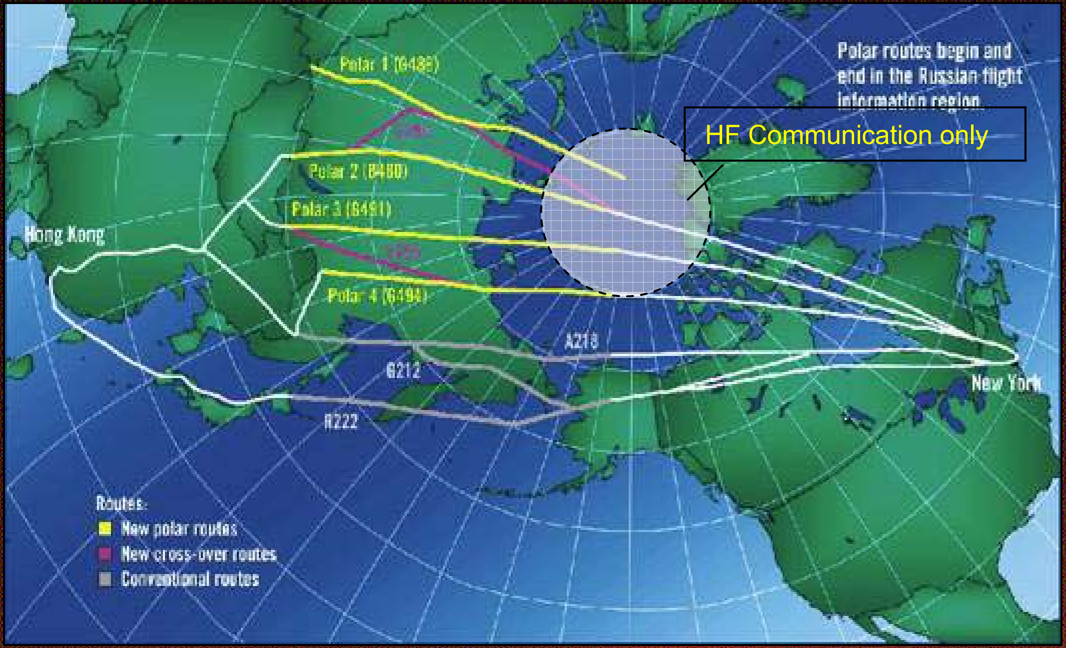
Image from NASA SOHO Satellite

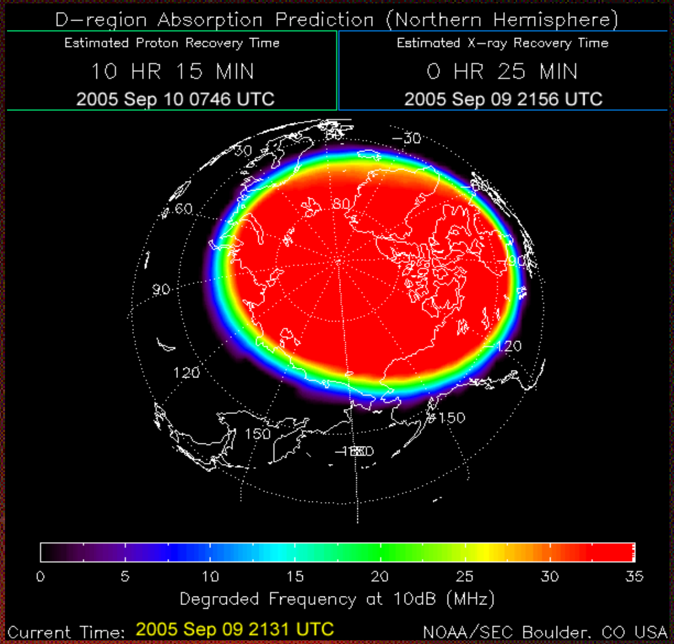
Loss of High Frequency (HF) communications during a solar flare, sunlit side of Earth only

San Francisco
Air Traffic Communications Center

NOAA Radio Absorption Plot

Airlines and the Polar Routes





- Flights rely on HF (3 – 30 MHz) communication inside the 82 degree circle.
- Federal Aviation Regulation Sec. 121.99 – aircraft must have two-way radio communication over the entire route with dispatch office and air traffic control.
- Airlines will often re-route flights away from polar routes during radiation and geomagnetic storms at a cost that can exceed $100,000 per flight.

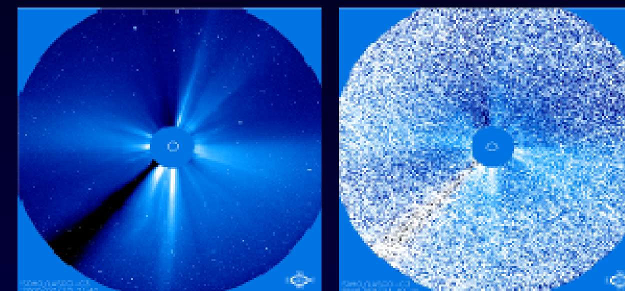
Geomagnetic Storm Effects
March 1989
Hydro Quebec Loses Electric Power for 9 Hours

Energetic Particle Effects

Spacecraft Systems

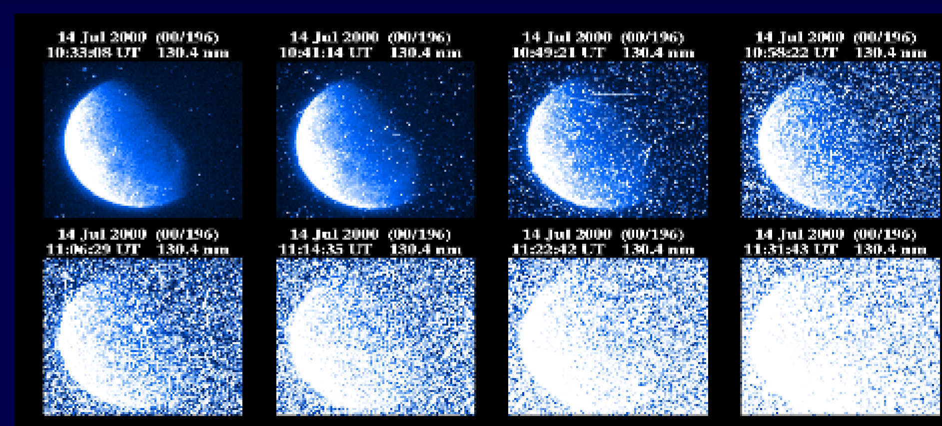
- Systems affected
  - Spacecraft electronics
    - Surface Charging and Discharge
    - Single Event Upsets
    - Deep Dielectric Charging
  - Spacecraft imaging and attitude systems

SOHO Satellite Image Degradation



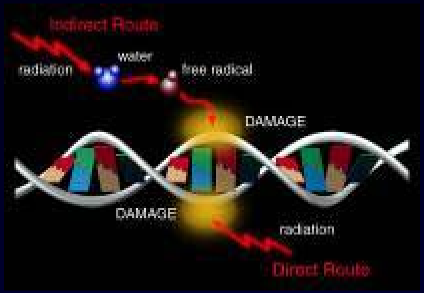
Spacecraft Surface Charging (NASA animation)

Polar Satellite Image Degradation



Energetic Particles Effects

Radiation Hazard



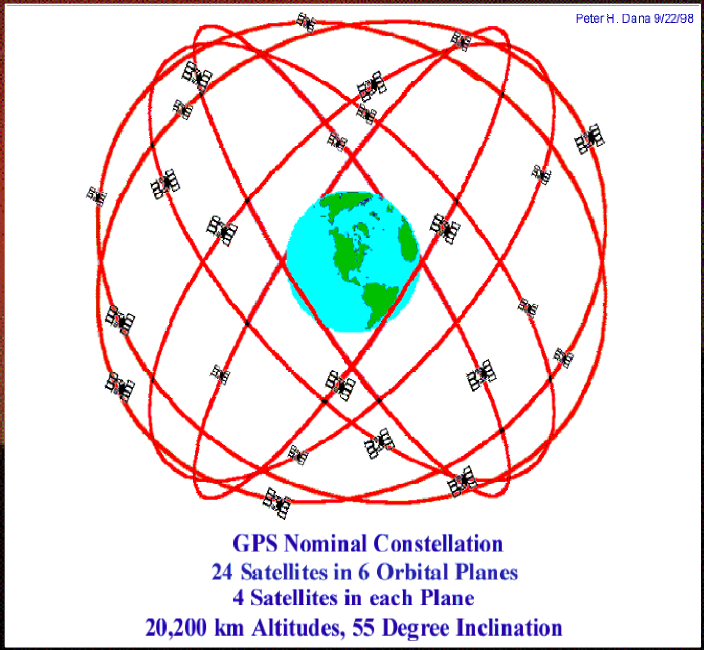
Health Hazards from Energetic Particles

- **Humans in space**
  - **Space Shuttle, International Space Station, missions to Mars**
- **Humans in aircraft**
  - **Concorde carried radiation detectors**
  - **Passengers may receive radiation doses equivalent to 10’s of chest X rays.**

NASA Video Clip

GPS Customers

- Deep-sea drilling operations
- Surveying companies - land surveying, topographic work, and property boundary analysis
- FAA WAAS
  (Wide-Area Augmentations System)
- Various DoD operations.

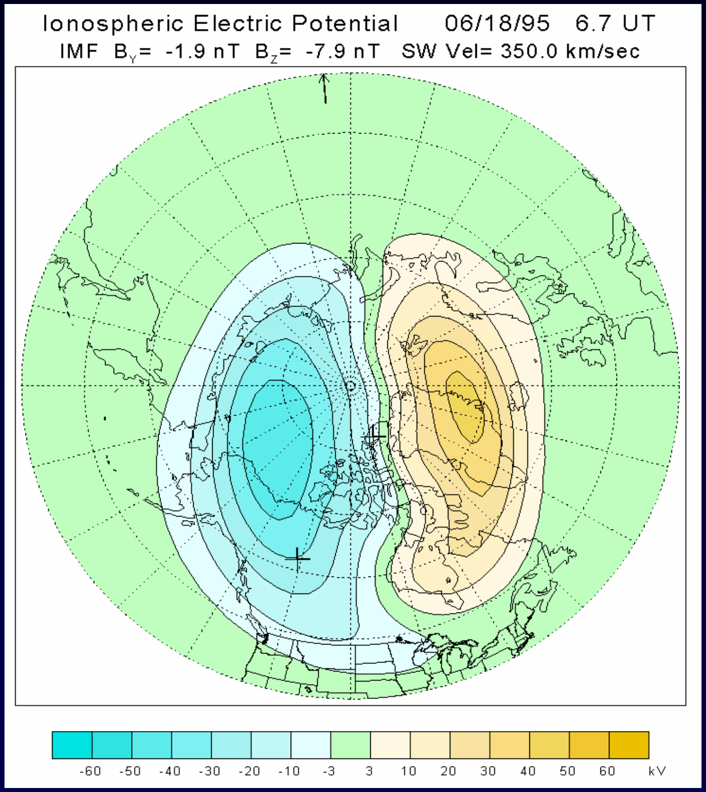


Magnetospheric Forcing during Geomagnetic Storms

Dynamic auroral precipitation pattern

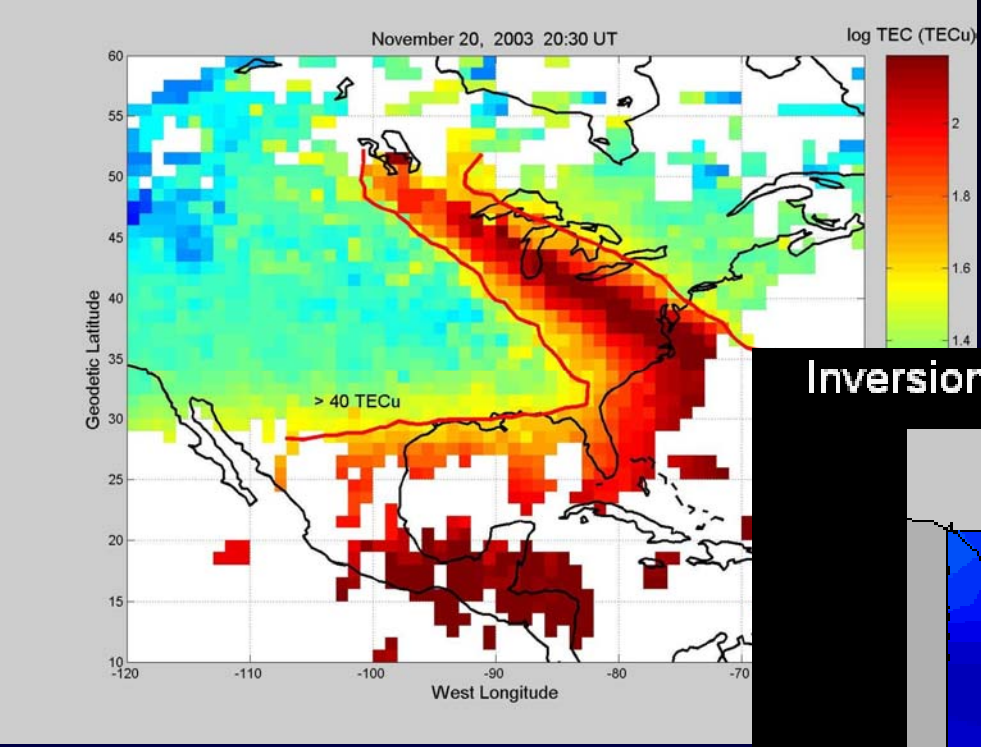
QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

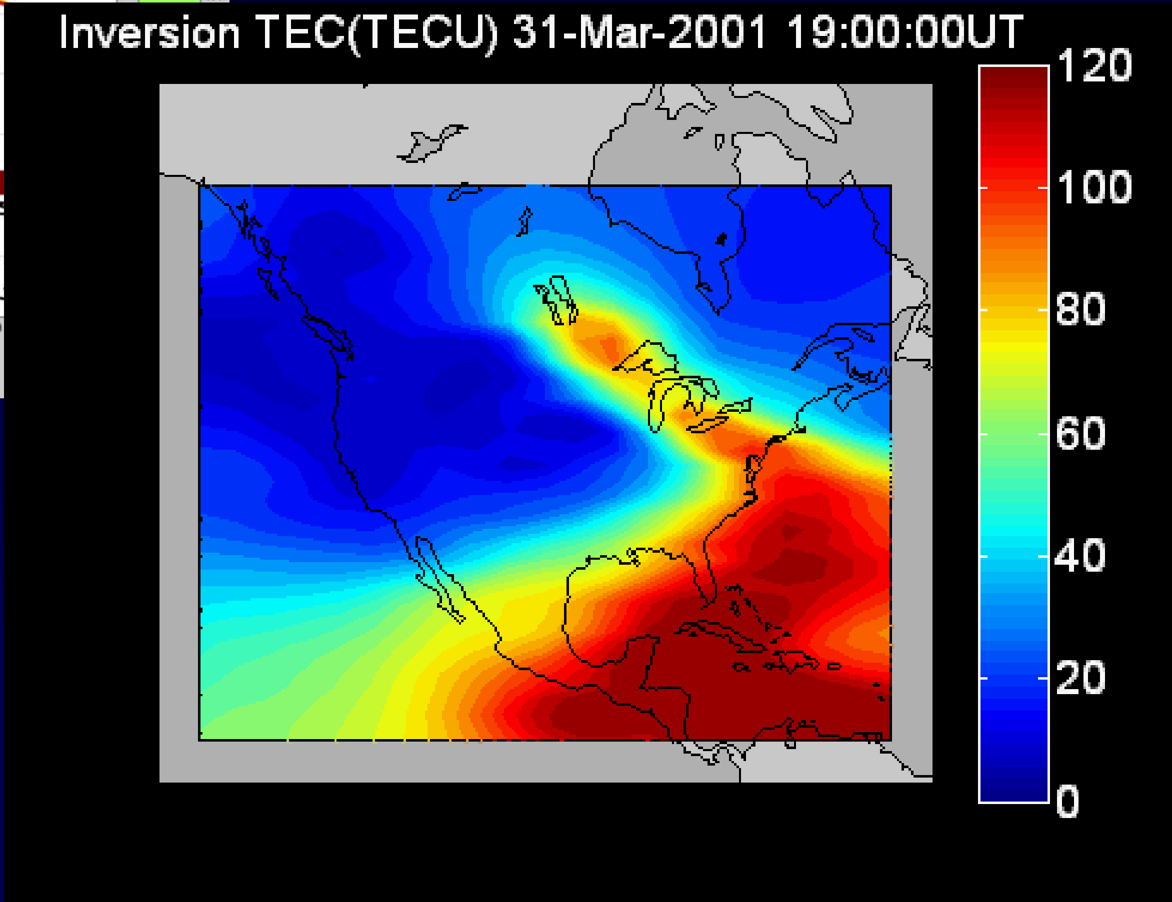
Electric field patterns driven by the solar wind:

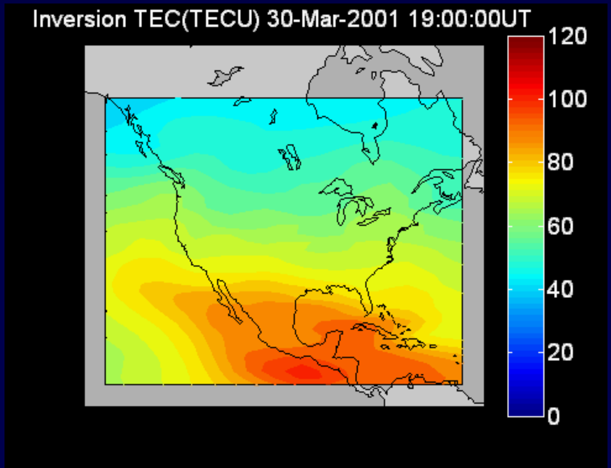


New consistent storm features:

e.g. SED

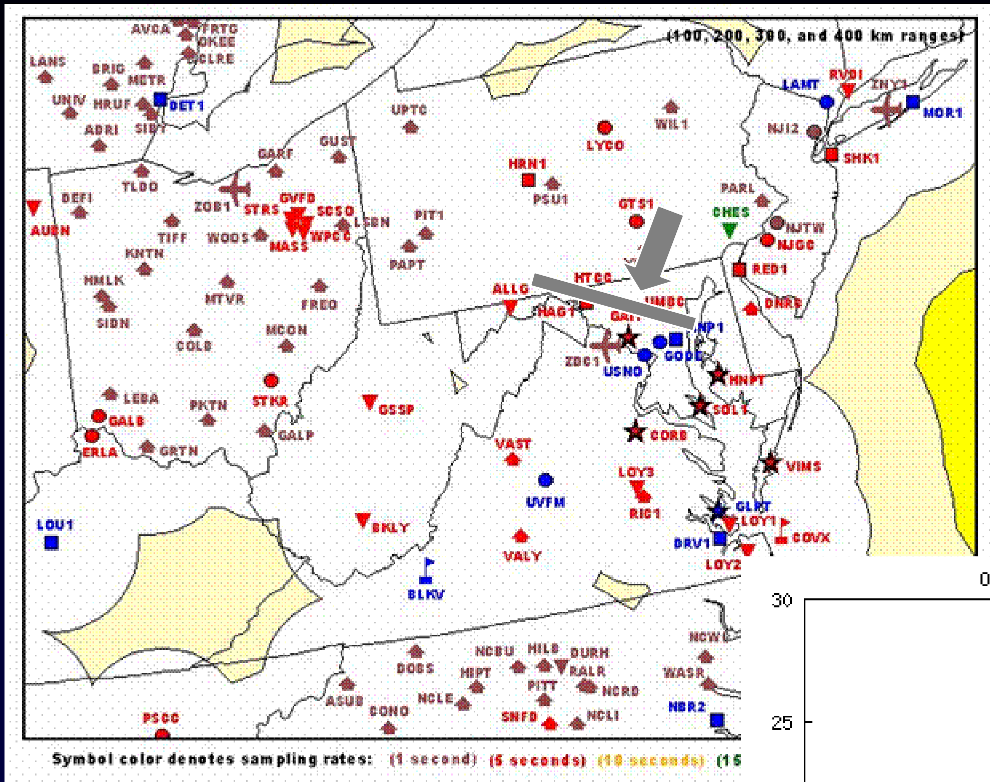


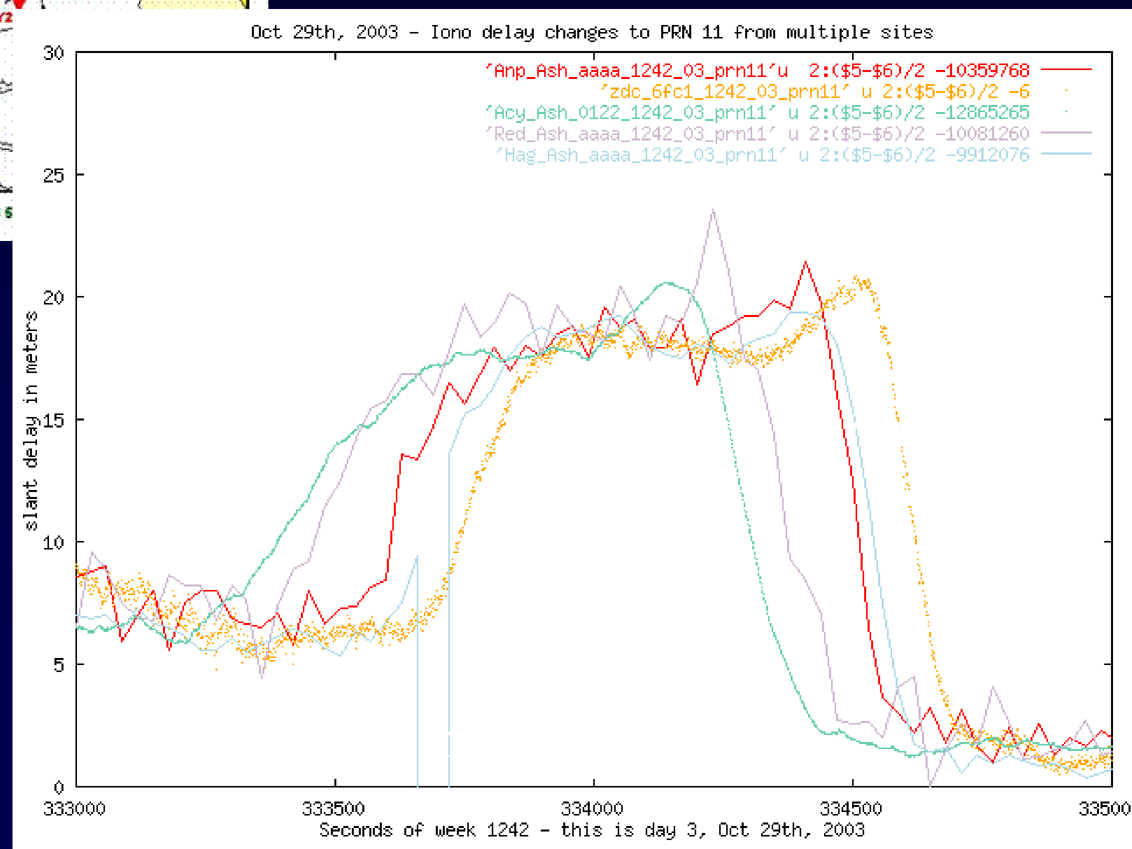




One of the challenges:

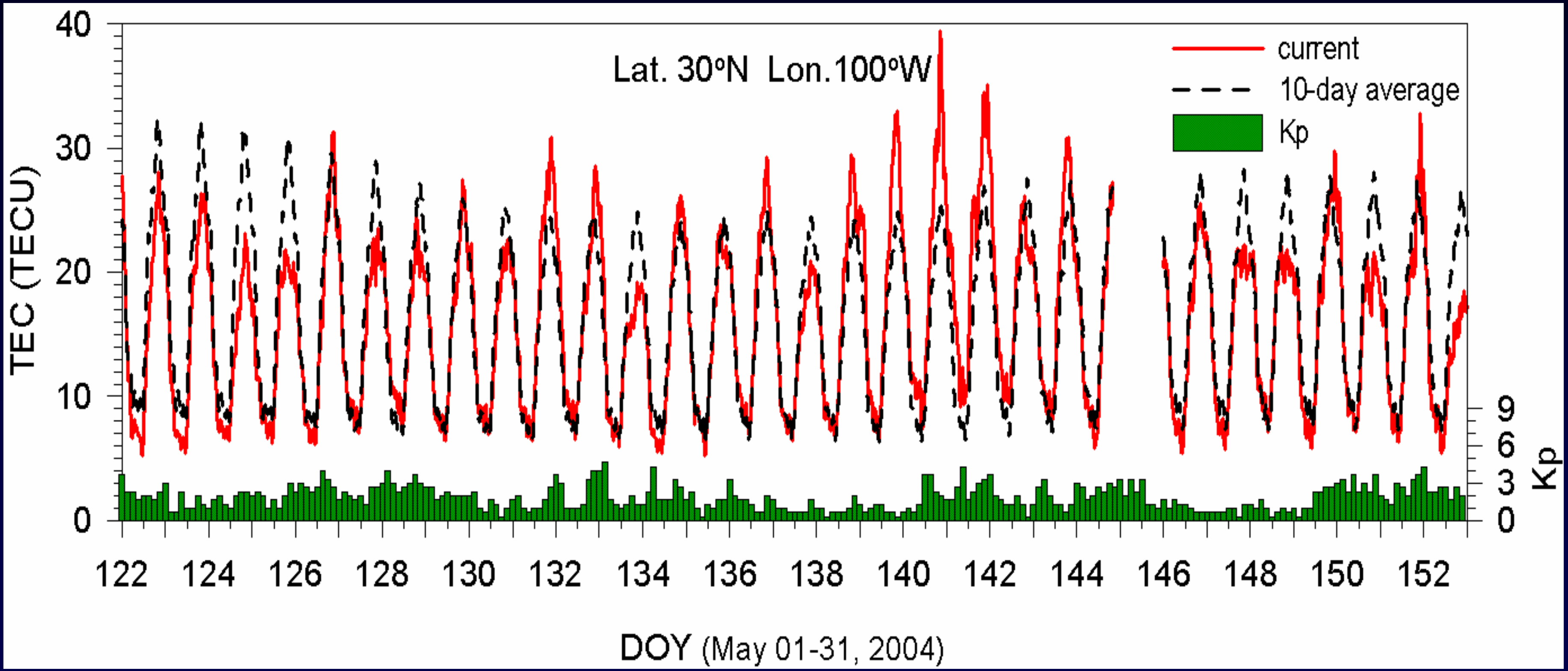
October 29th, 2003
stationary “walls” of TEC compromise integrity of LAAS



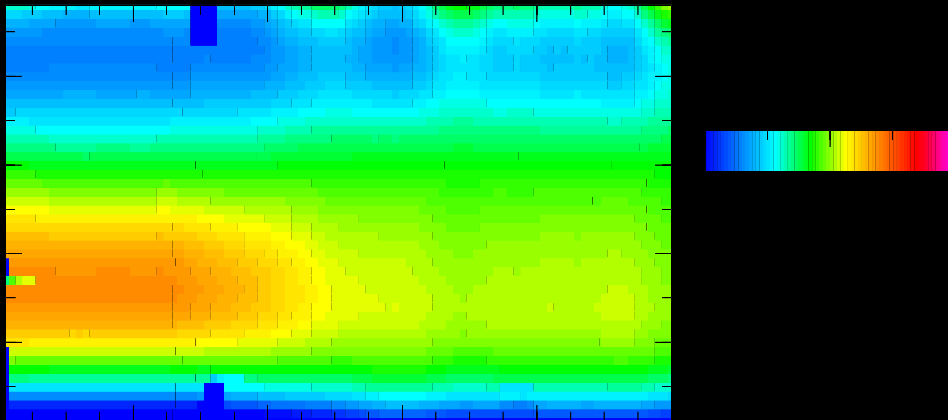


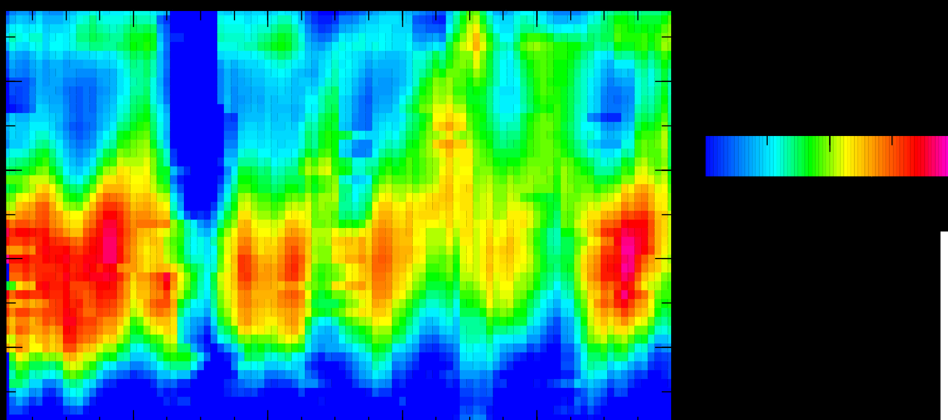
TEC “walls”:
130 TEC units over 50 km
20 m of GPS delay;
walls move 100 to 500 m/s

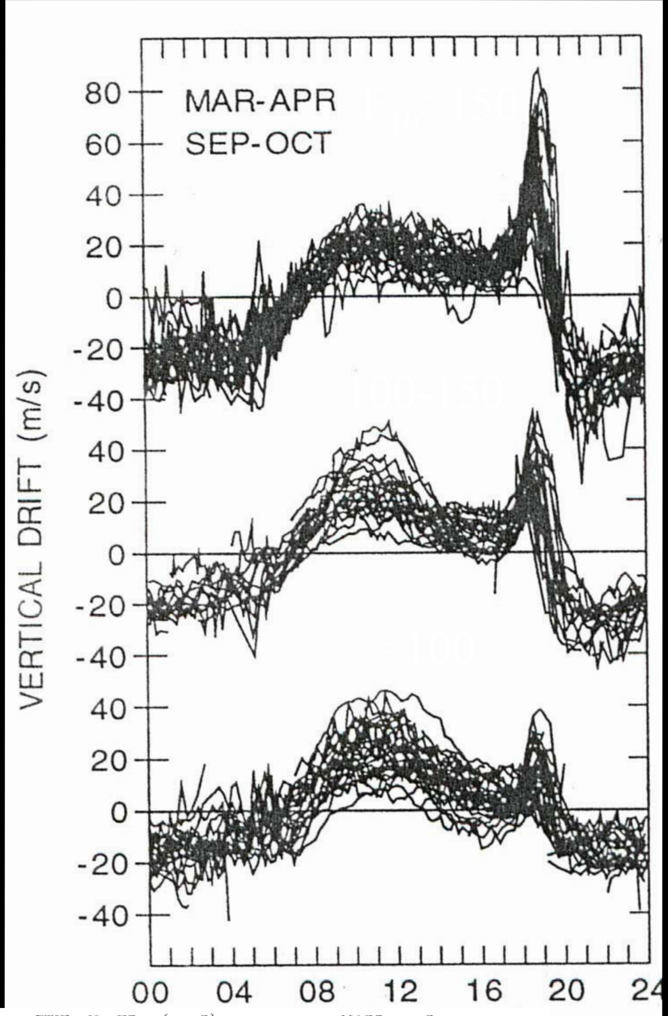
Day-to-day variability in ionospheric total electron content

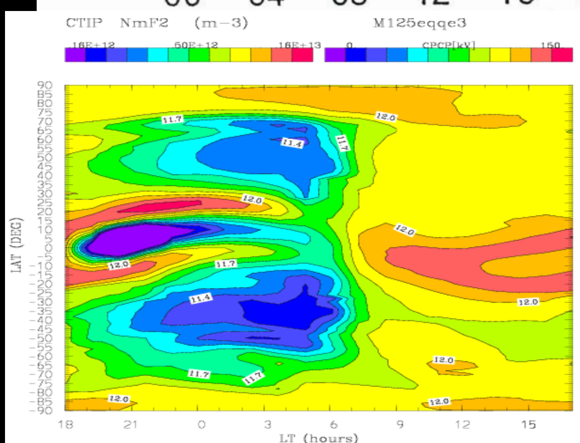


Multi-day periodicities



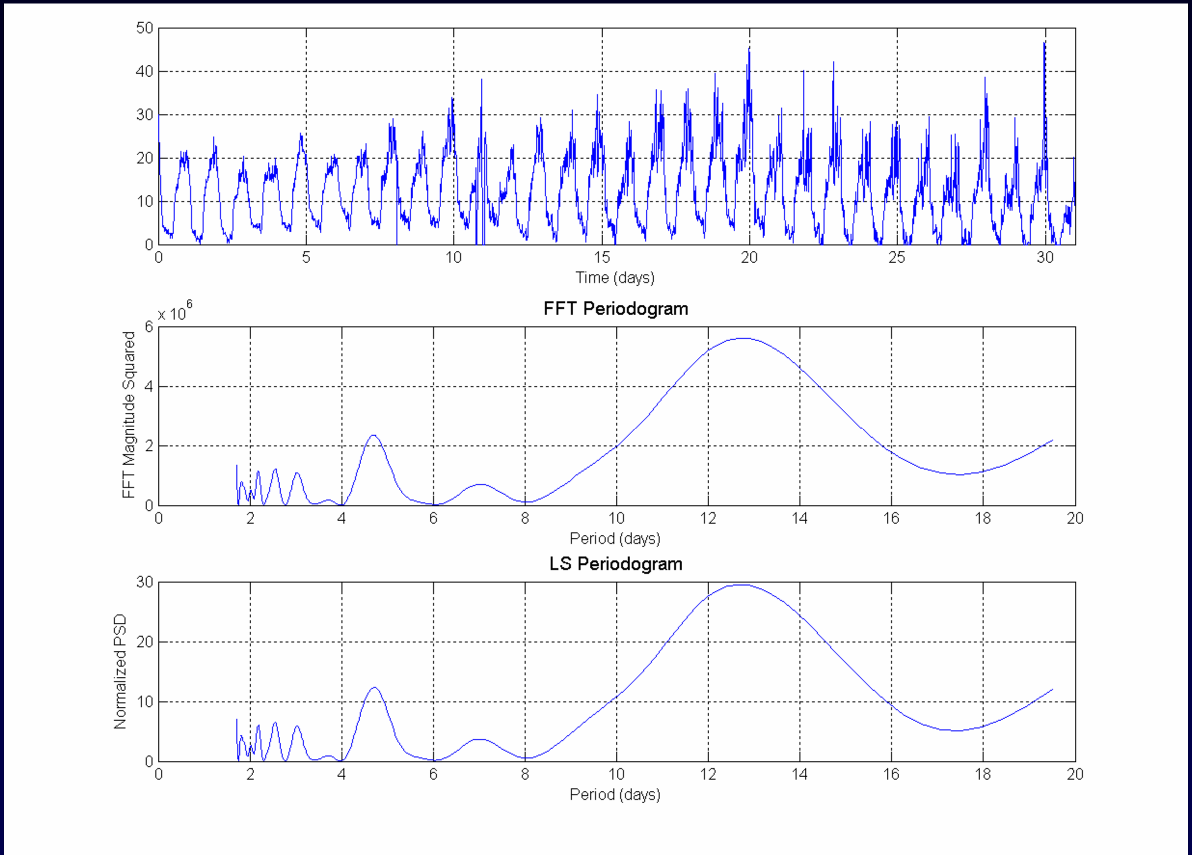


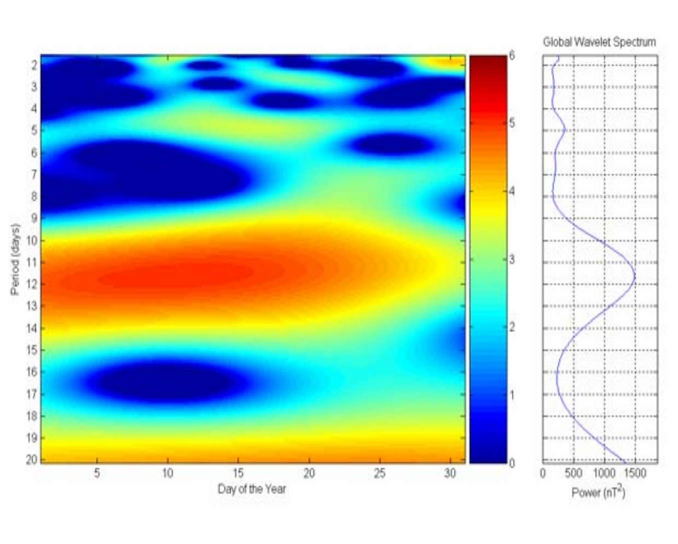


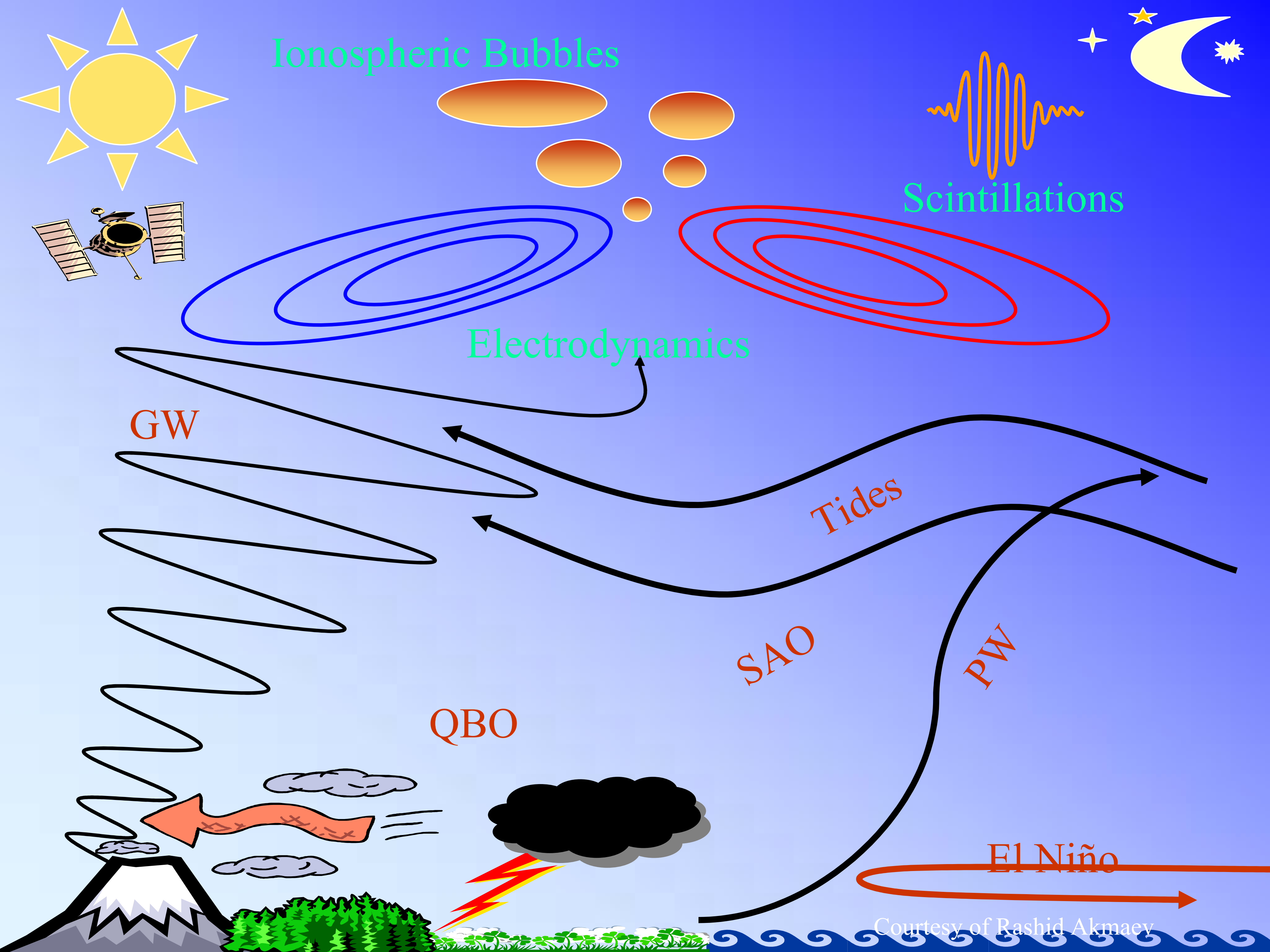


Jan Sojka, 2003

Spectral Analysis






Ionospheric Bubbles
Scintillations
Electrodynamics
GW
Tides
SAO
PW
QBO
El Niño
Courtesy of Rashid Akmaev

Integrated Dynamics through Earth's Atmosphere (IDEA)

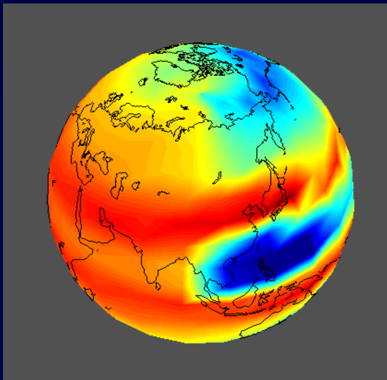
A collaboration between EMC and SEC to integrate meteorological and space weather

Initially target upward coupling: the response of the upper atmosphere to lower atmosphere forcing

Later implement data assimilation through whole atmosphere (including CORS-GPS data) for tropospheric and ionospheric forecasting

Tim Fuller-Rowell, Rashid Akmaev, Mihail Codrescu, Naomi Maruyama, and Fei Wu

NOAA Space Environment Center and CIRES University of Colorado



Data Assimilation at SEC

US-TEC Product: http://www.sec.noaa.gov/ustec

- **Current NOAA capability for characterizing the total number of free electrons (TEC) in the ionosphere, with parallel input data streams for reliability**
- **Since 2004, a product characterizing the ionospheric TEC over the continental US (CONUS) has been running in real-time at NOAA's Space Environment Center (SEC)**
- **The ionospheric data assimilation model uses a Kalman filter and ingests ground-based GPS data to produce 2-D maps of total electron content over the CONUS**
- **Product evolved from a collaboration between SEC and NOAA's National Geodetic Survey (NGS), National Geophysical Data Center (NGDC), and Forecast Systems Laboratory (FSL)**

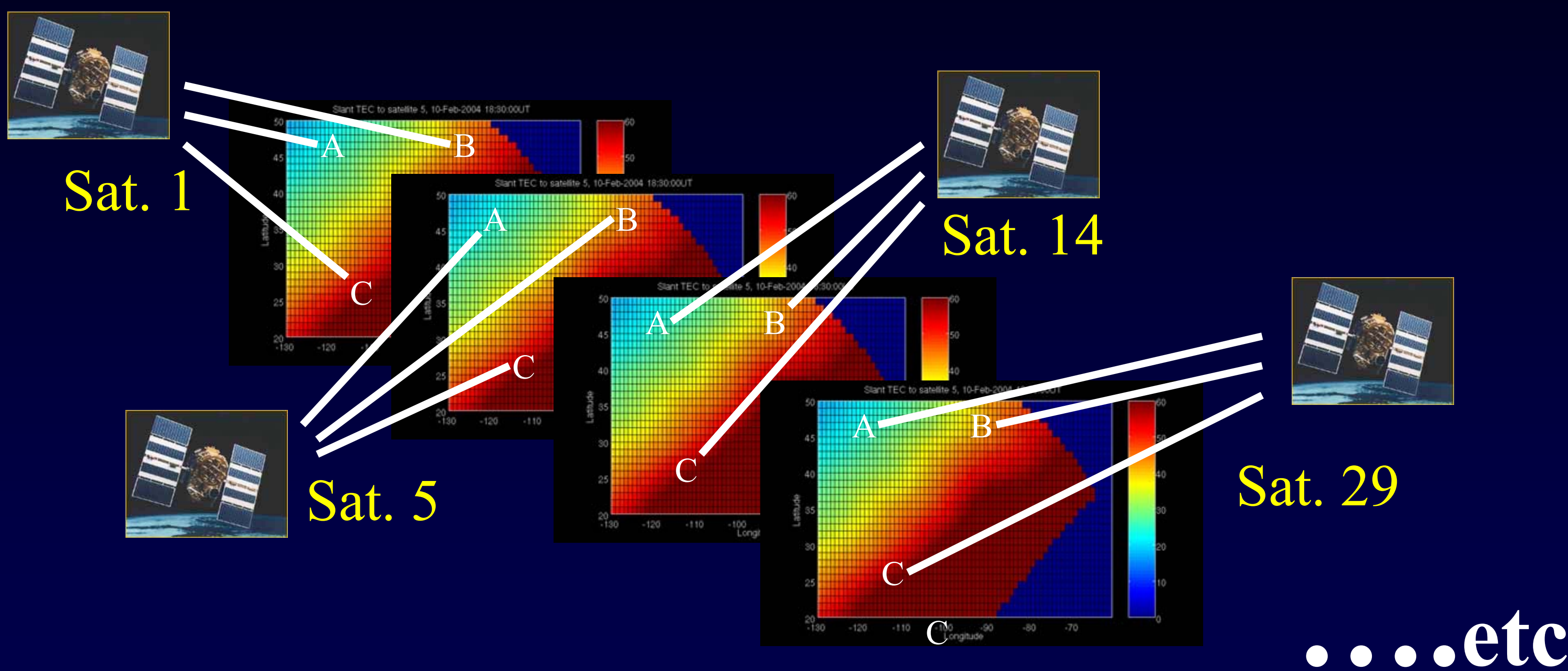
Primary Product:

Real-time ionospheric maps of total electron content every 15 minutes. Currently uses about 60 real-time GPS stations from the CORS network

QuickTime™ and a
TIFF (PackBits) decompressor
are needed to see this picture.

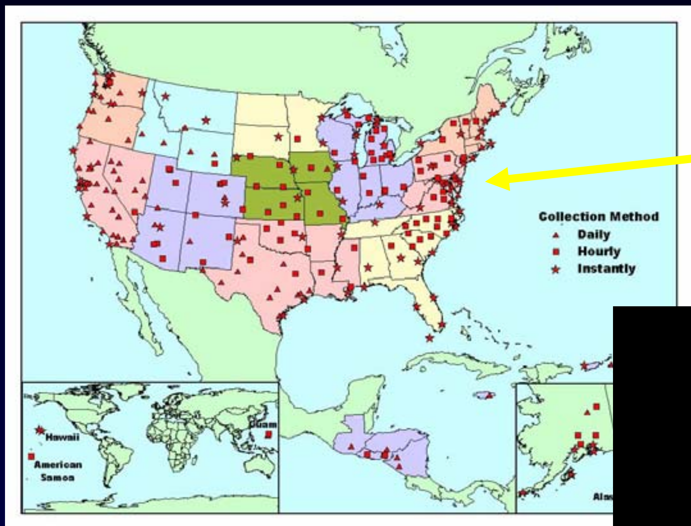
Slant-Path TEC Maps

•Work horse of the product are 2-D maps of slant path TEC over the CONUS for each GPS satellite in view updated every 15 minutes
•Provides the information needed to estimate the group delay or phase advance for the GPS signals anywhere in the CONUS

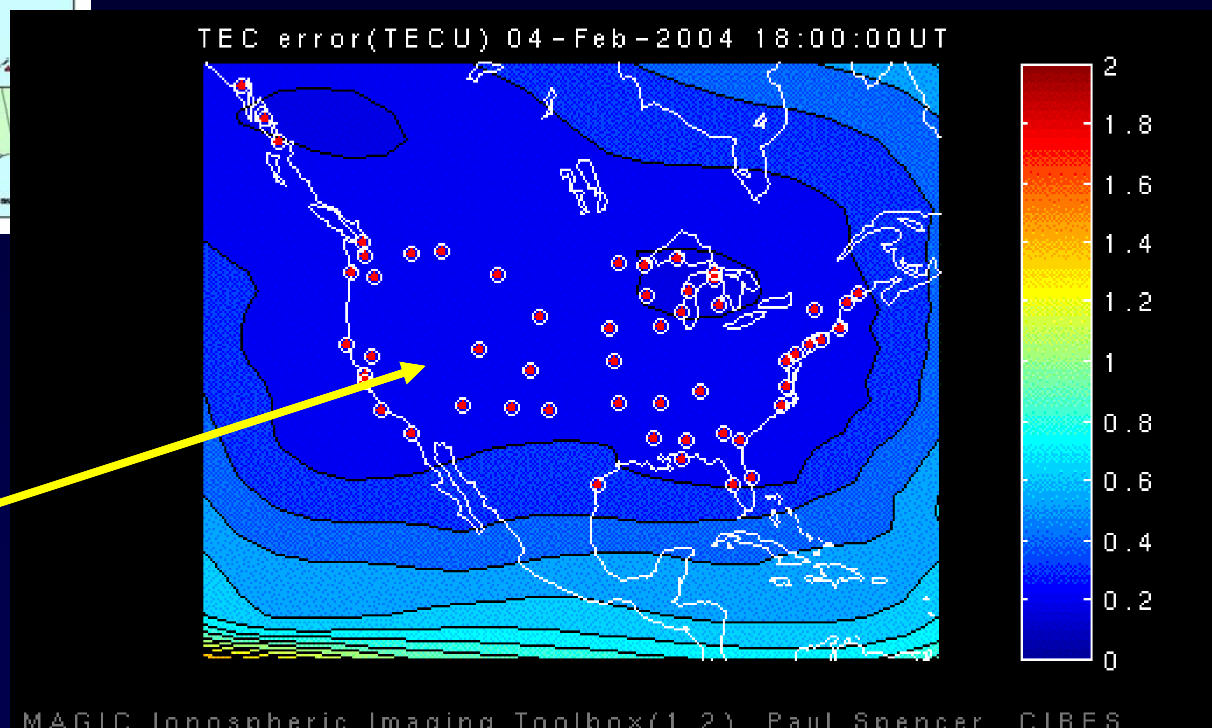


Applications:
Ionospheric correction for single frequency GPS; NDGPS positioning; dual-frequency integer ambiguity resolution for rapid centimeter accuracy positioning

Real-Time Stations



Data from ~500 CORS (Continuously Operating Reference Stations) GPS dual-frequency receivers are collected by NGS (National Geodetic Survey)



Currently uses over 100 US Coast Guard, NOAA, and Canadian stations

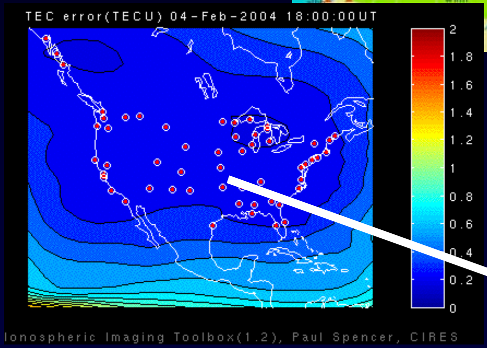
The Kalman Filter and extracting "information"

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

Expansion in global ground-based GPS networks combined with COSMIC to improve global specification

Canada

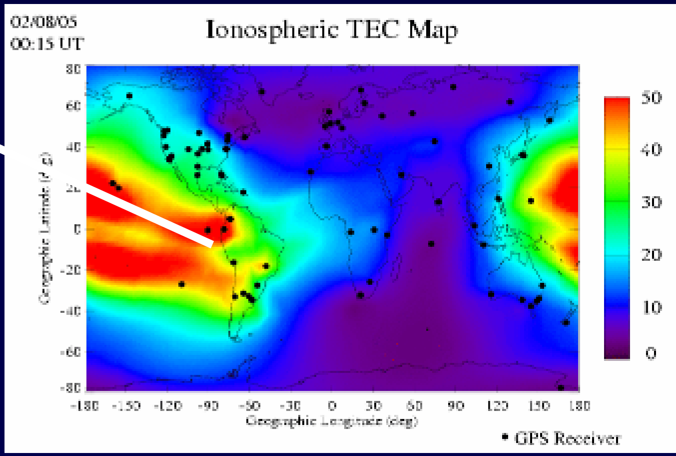
Europe (EUREF)



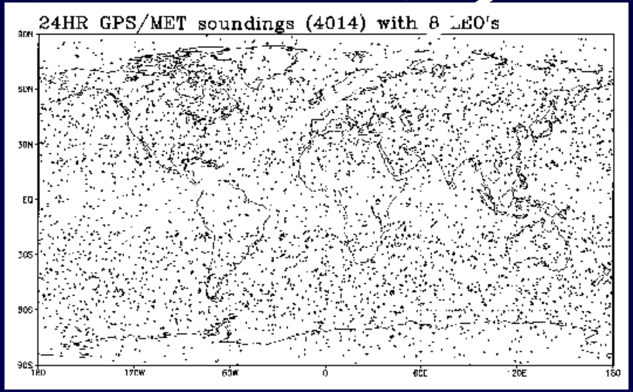
USA

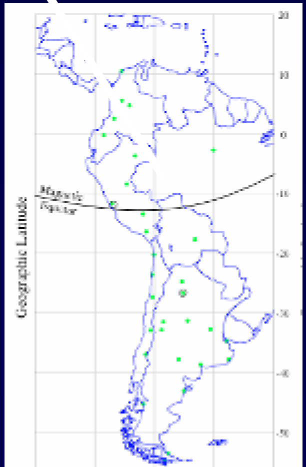
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

JPL



COSMIC (GPS occultations)

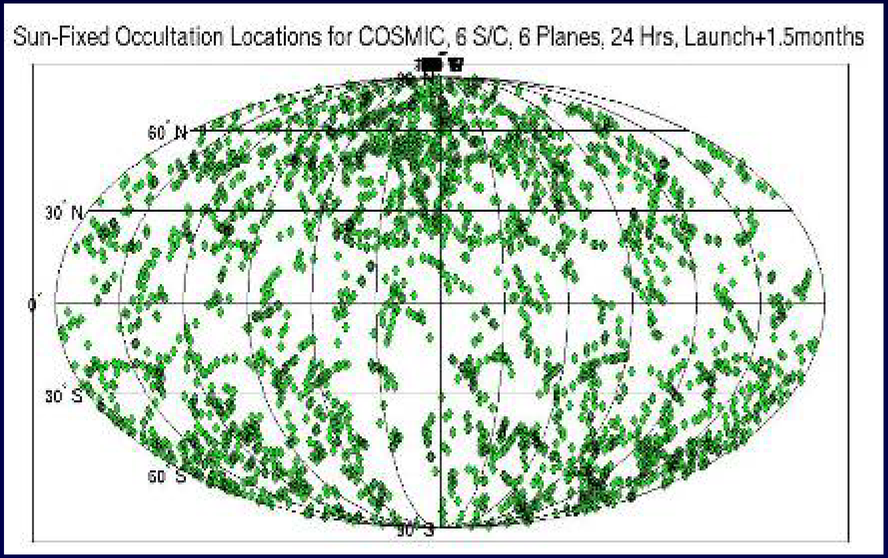


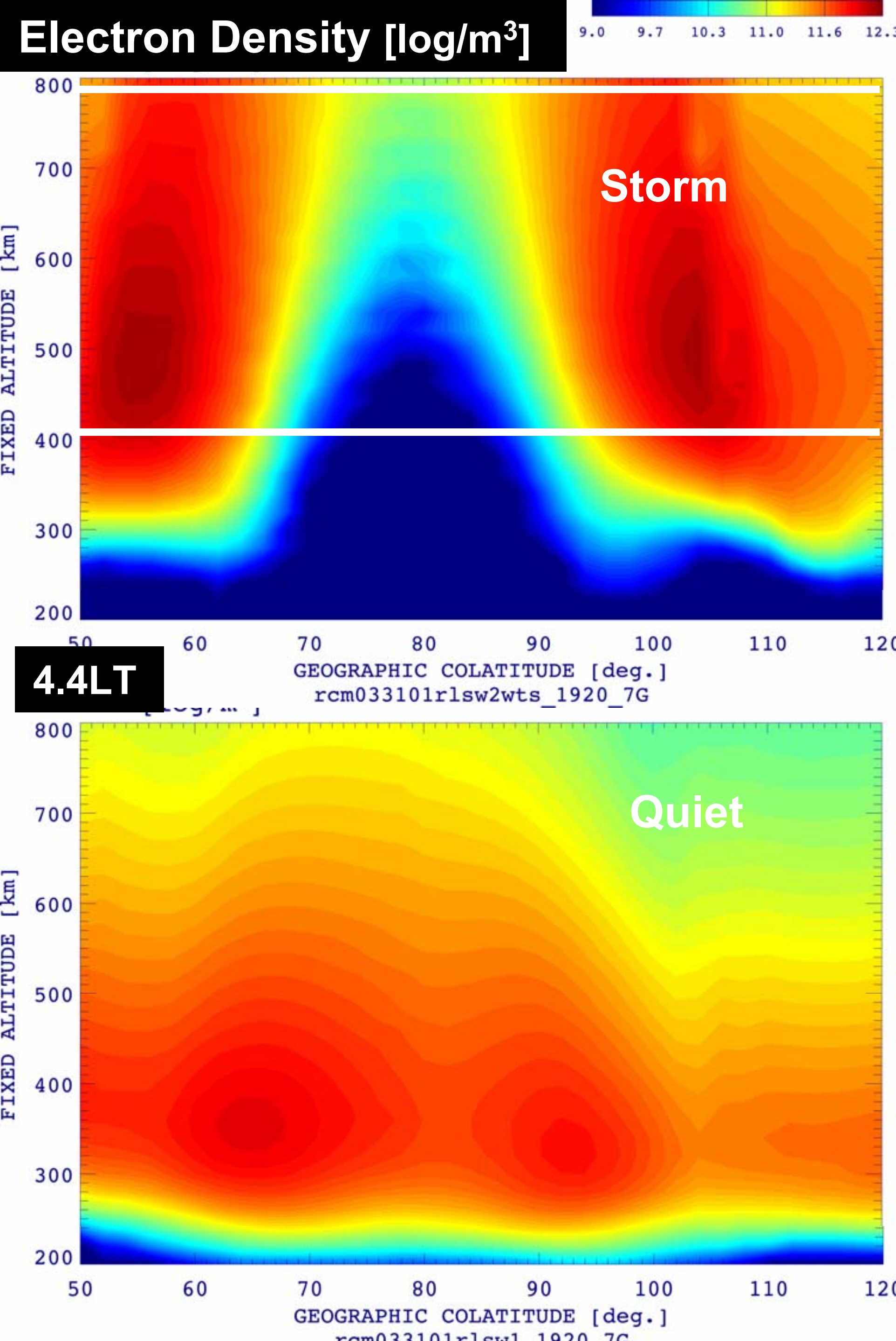


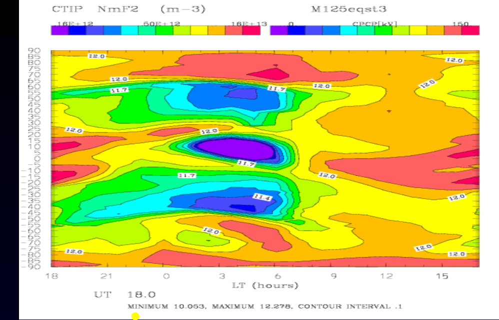
South America

Potential of Radio Occultations

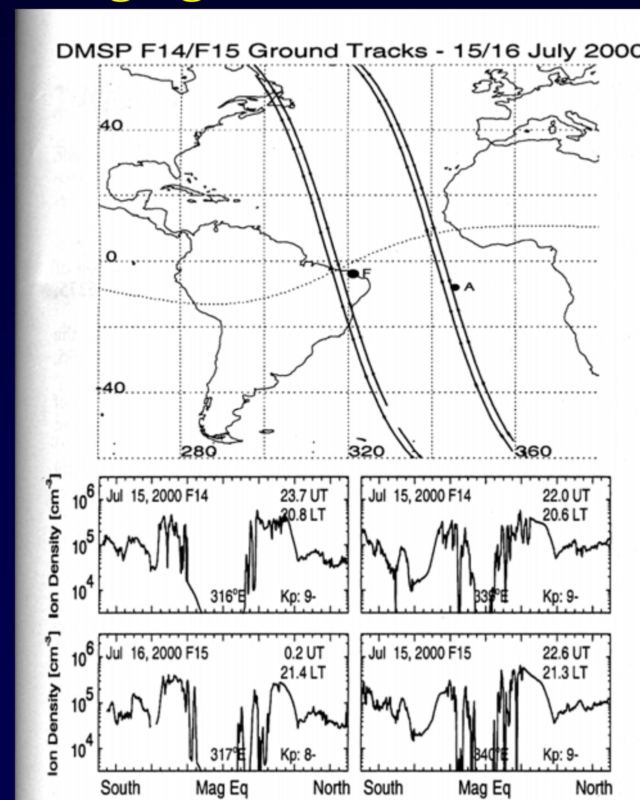
- Provides orthogonal look direction complementing ground-based GPS for ideal tomography imaging
- Full vertical profile
- All weather
- Day and night
- No instrument drift
- Global coverage







- Understanding the massive restructuring of the ionosphere during geomagnetic storms
- "Imaging" 3D structure essential



Operational Value to NOAA (if data are timely!)

- Demand for ionospheric services is growing
- Radio occultation provides a uniquely helpful dataset for space weather monitoring
- Significant improvement in characterizing vertical structure of ionosphere has been demonstrated when RO data are assimilated
- Significant impact on SEC ionospheric products

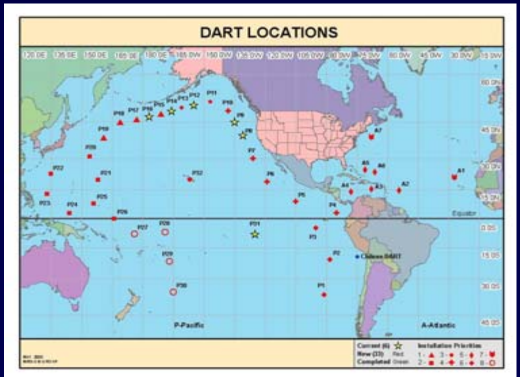
Summary

- Space weather is mainly driven by the sun for the extreme events (flares, geomagnetic storms, solar radiation events)
- Day-to-day changes in the upper atmosphere and ionosphere can arise from lower atmosphere processes - tides, planetary and gravity waves
- Data assimilation is now being used for space weather specification particularly in the ionosphere (forecasting is still a challenge)
- New satellite data sources will enable global ionospheric specification

Future Plans for US-TEC

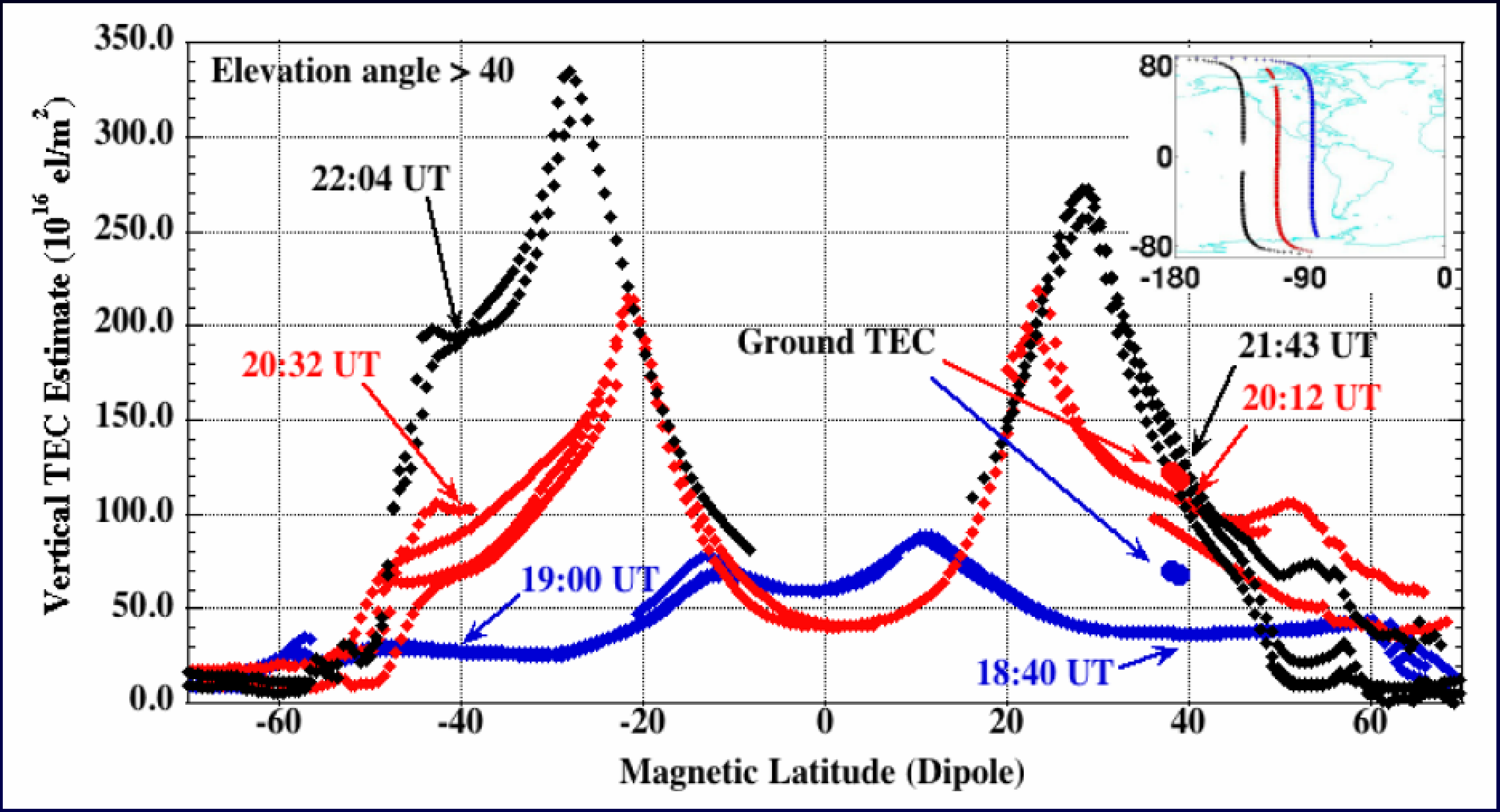
- Further increase number of stations over CONUS to ~120 (including NOAA-GSD and FAA-WAAS stations)
- Include Canadian stations to improve TEC on poleward side and provide values over North America

- Increase cadence to 5 minutes and reduce latency
- Provide short-term forecast (10 to 30 minutes) to bring up to, or just beyond, real-time
- Need sites to the south (Mexico and Caribbean)
- Buoys over oceans



- Positioning validation

CHAMP (400 km) OSEC: Halloween Storm



Mannucci et al 2005

How will COSMIC RO be used at SEC?
Future Capability

- Ingest radio occultation data into current and future assimilative models including Gauss-Markov, physics-based and Ensemble Kalman filters (EnKF) for specification and forecasting the space environment

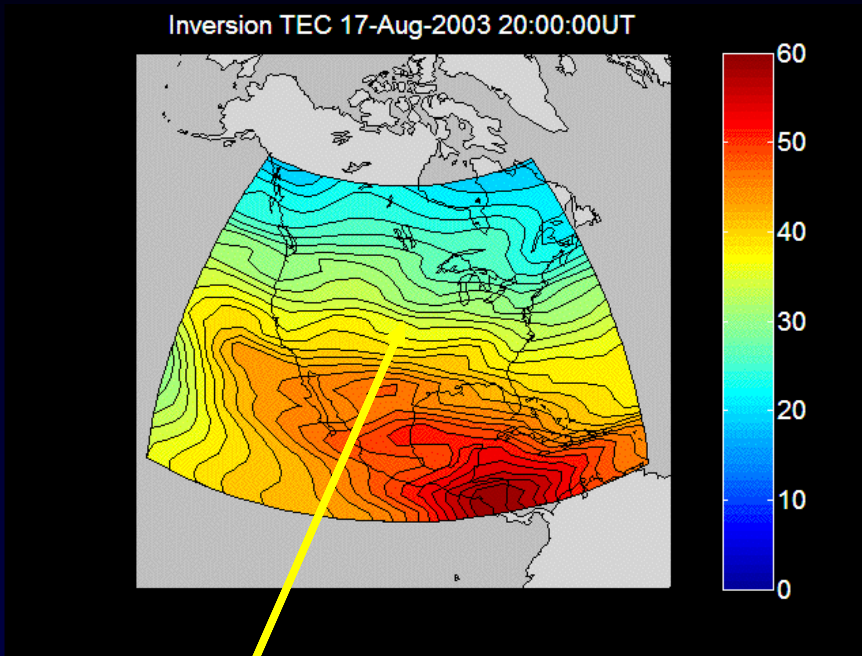
- US-Total Electron Content (US-TEC)
  - Regional Kalman filter data assimilation model
  - Driven by ground-based dual-frequency GPS
  - Already implemented at SEC
  - Could be modified to include RO

- Global Assimilation of Ionospheric Measurements (Utah State Univ.) Global Assimilative Ionospheric Model (Univ. Southern California/JPL)
  - GAIM I - Gauss-Markov Kalman Filter
  - GAIM II - Physics-based Kalman Filter
  - GAIM - USC
  - GAIM models already have the capability of ingesting radio occultations and other additional datasets
  - COSMIC I data ideal to test and validate utility of RO constellation in operations
  - GAIM I and II will be implemented operationally at AFWA
  - SEC backup or COOP for AFWA

Practicalities

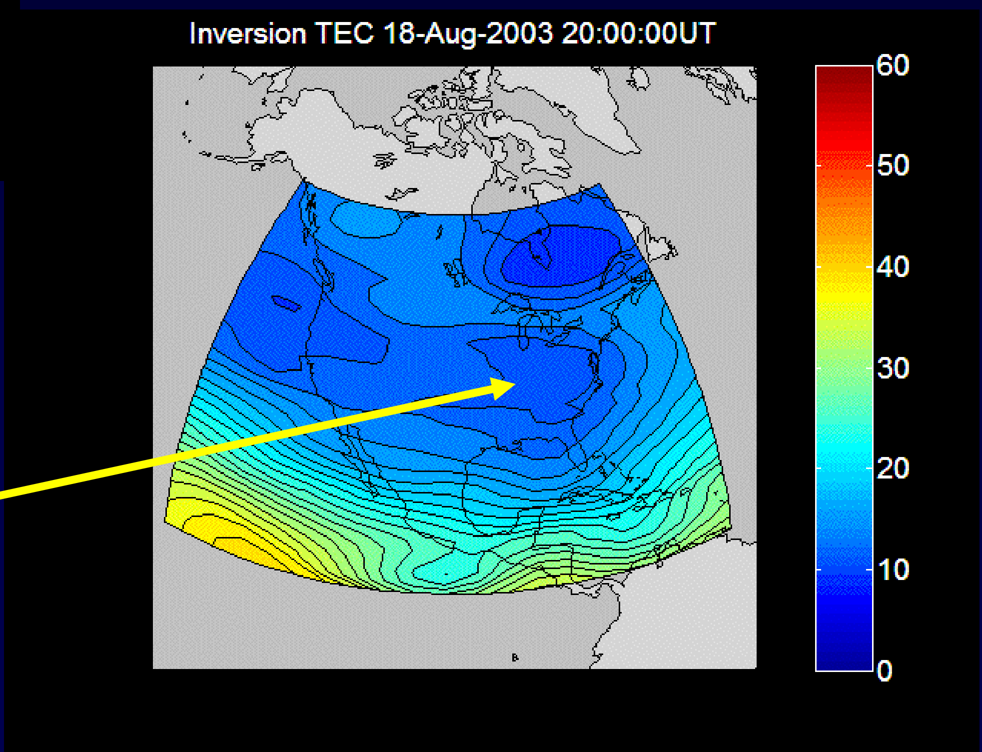
- Ionospheric data products from COSMIC available with about a 2 hour latency
- Ionospheric data products could be transferred to NESDIS from CDAC, with the BUFR files
- NESDIS possibly distribute to other NOAA and DoD real-time users (SEC, AFWA, NGDC, etc)
- SEC to perform an impact analysis using global US-TEC or GAIM-I type models
- Radio occultation provides a unique dataset for space weather applications
- Expect significant improvement in characterizing vertical structure of ionosphere
- Possible global distribution available to users with 2-hour latency for situational awareness (timeliness is key for the ionosphere for quantitative value)

TEC can also be wiped out at mid-latitudes



The geomagnetic storm on Monday August 18th 2003 wiped out the normal daytime peak in electron density over North America

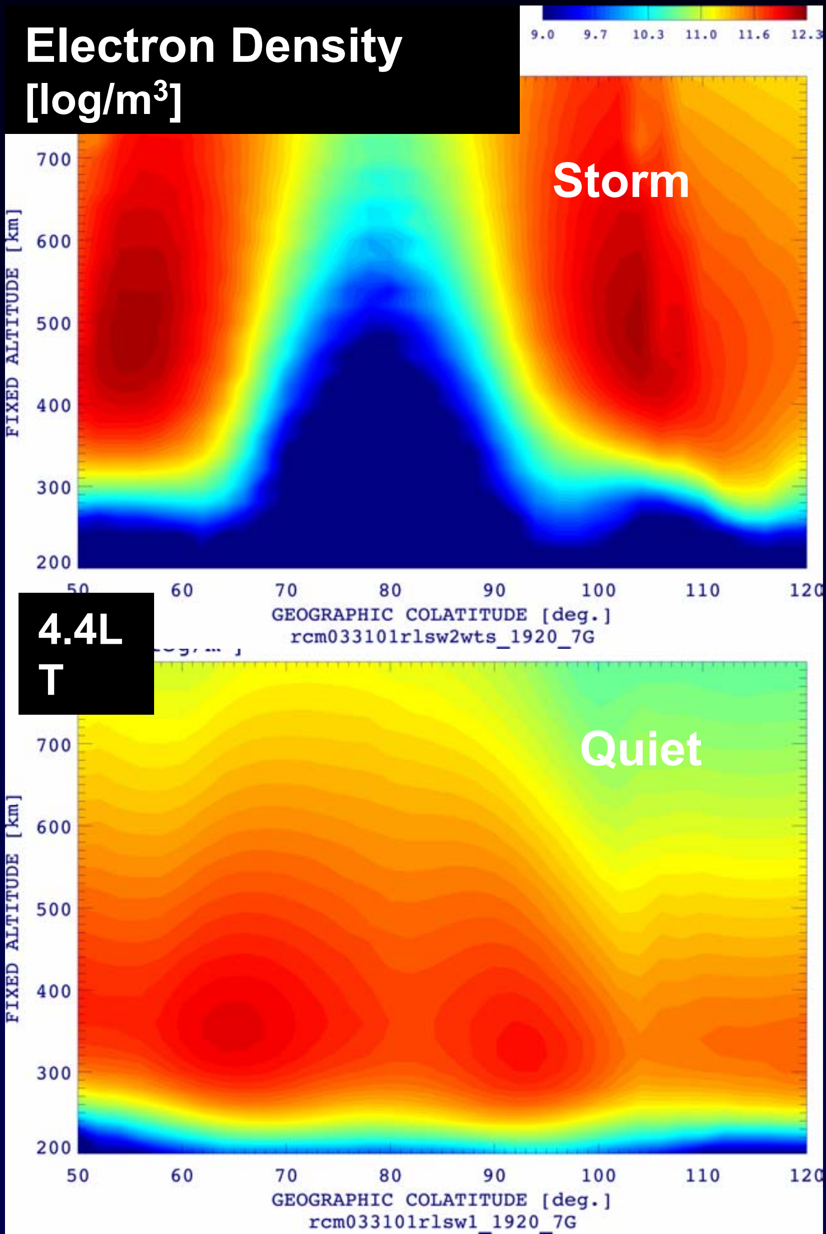
Quiet-day maximum electron density on August 17th

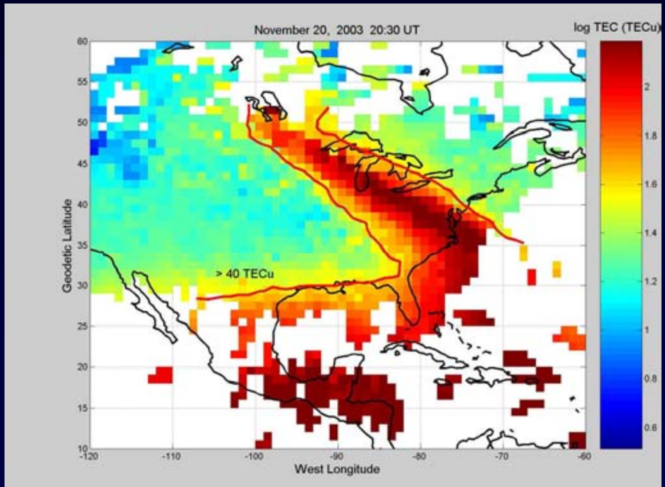


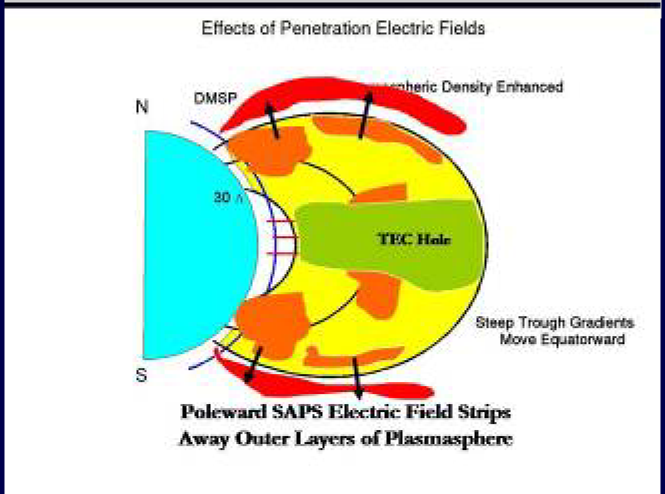
Ionospheric depletion on the 18th during the storm

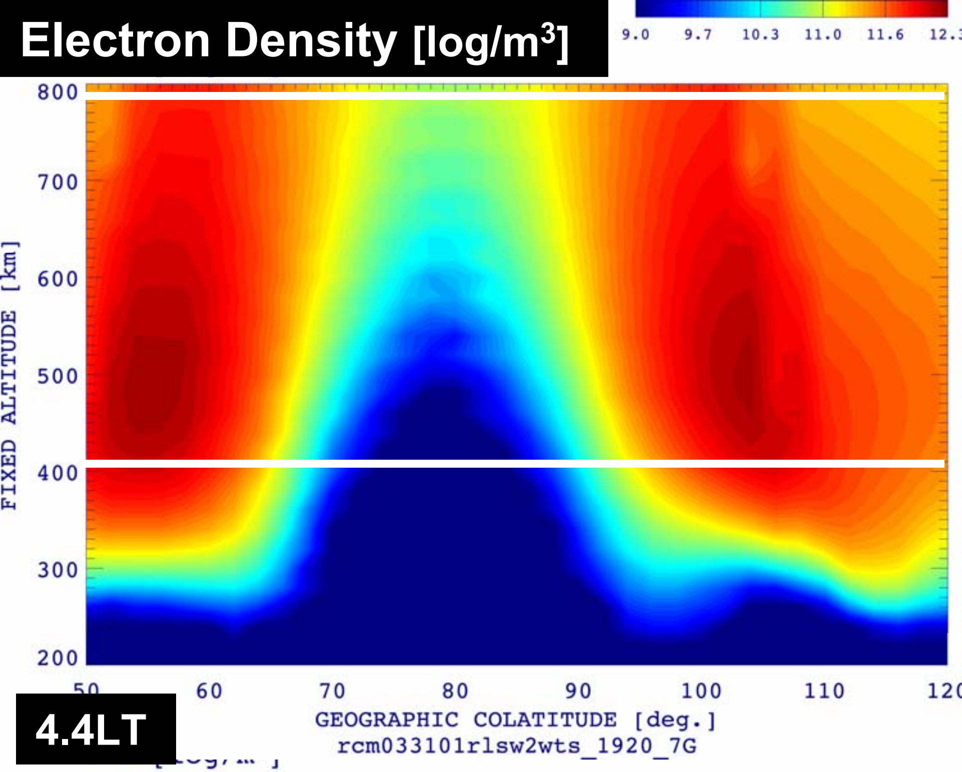
⇐ Storm Research:

- Understanding the massive restructuring of the ionosphere during geomagnetic storms
- "Imaging" 3D structure essential

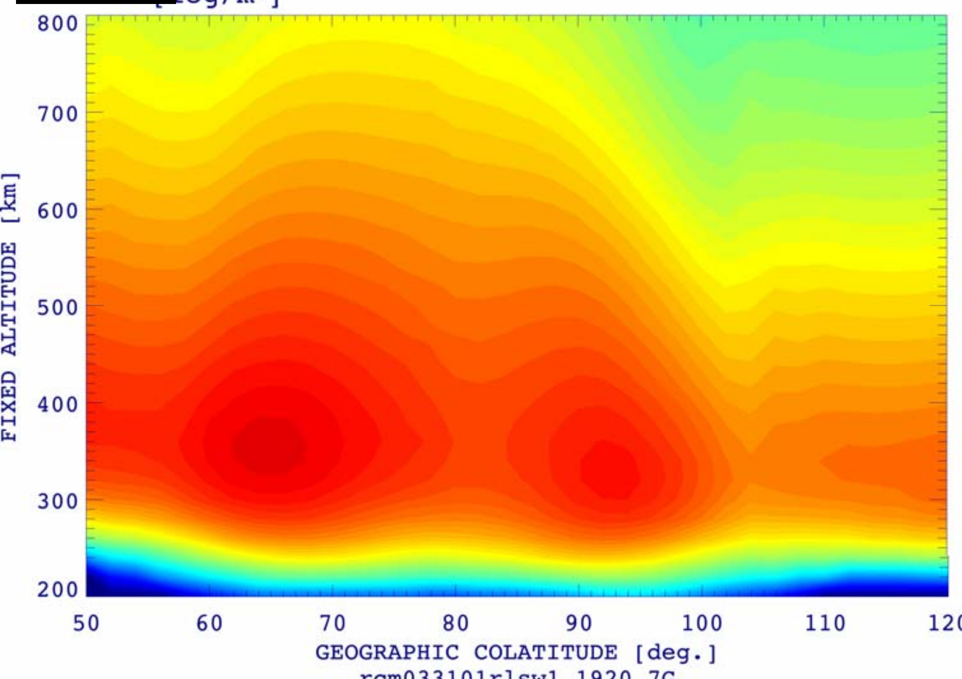






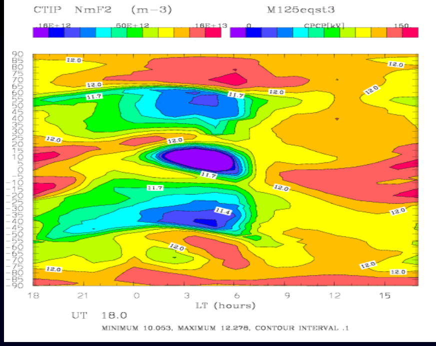


4.4LT



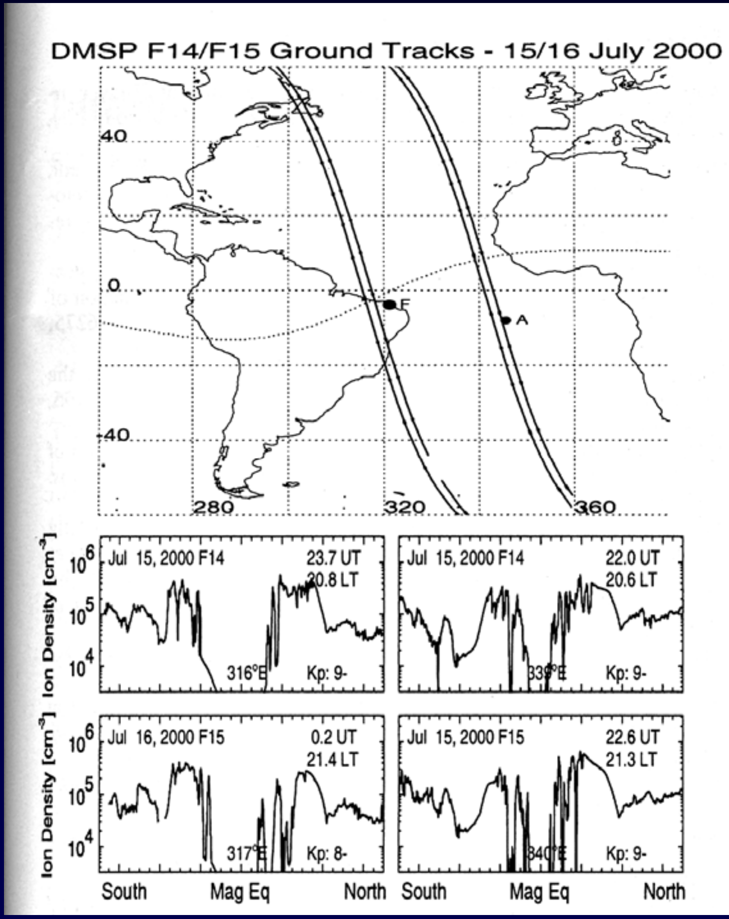
⇐ Storm

“Bite-outs”



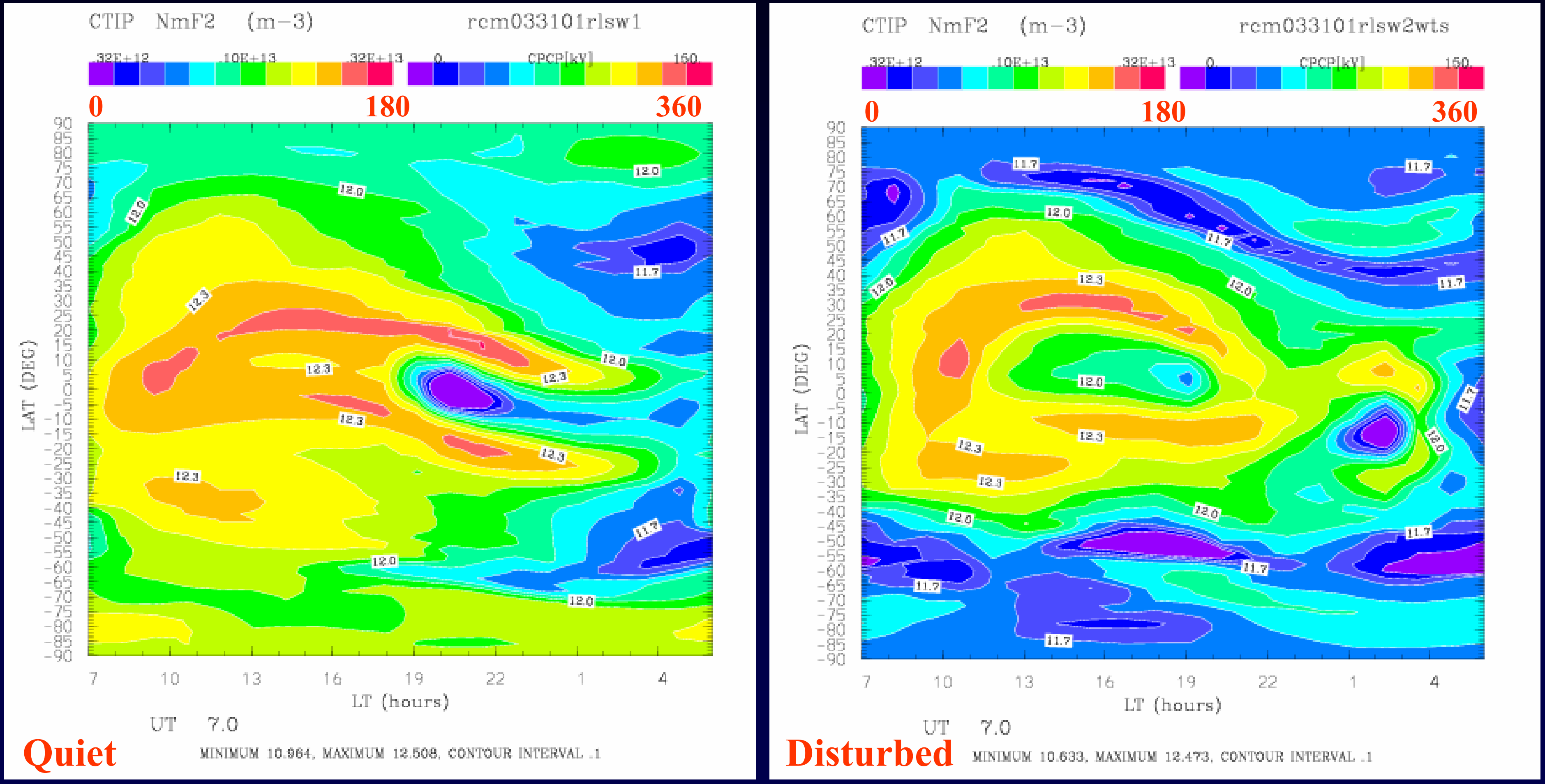
⇐ Storm

⇐ Quiet

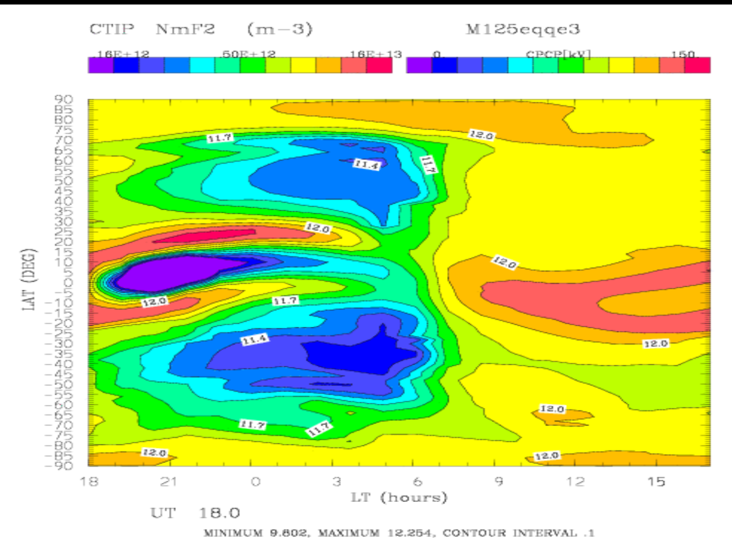


Basu et al. 2001

Prompt E Field Penetration

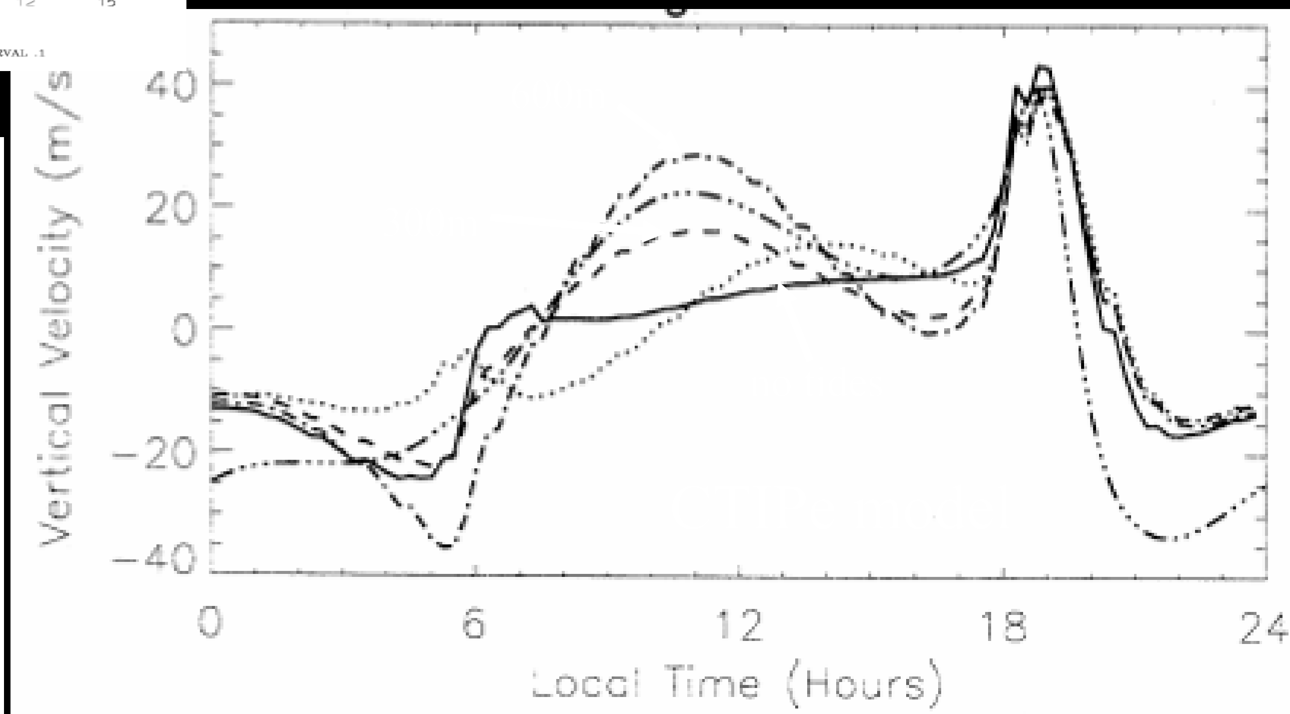


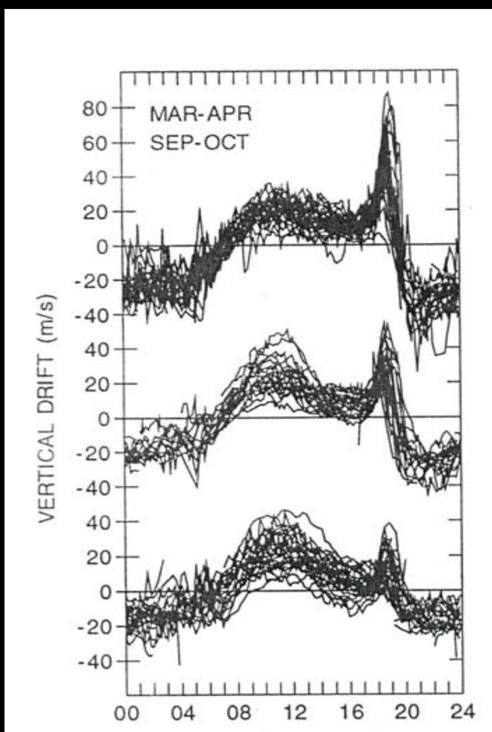
Source of Electrodynamics Variability on the Dayside



NmF2

vertical ion drift at magnetic equator



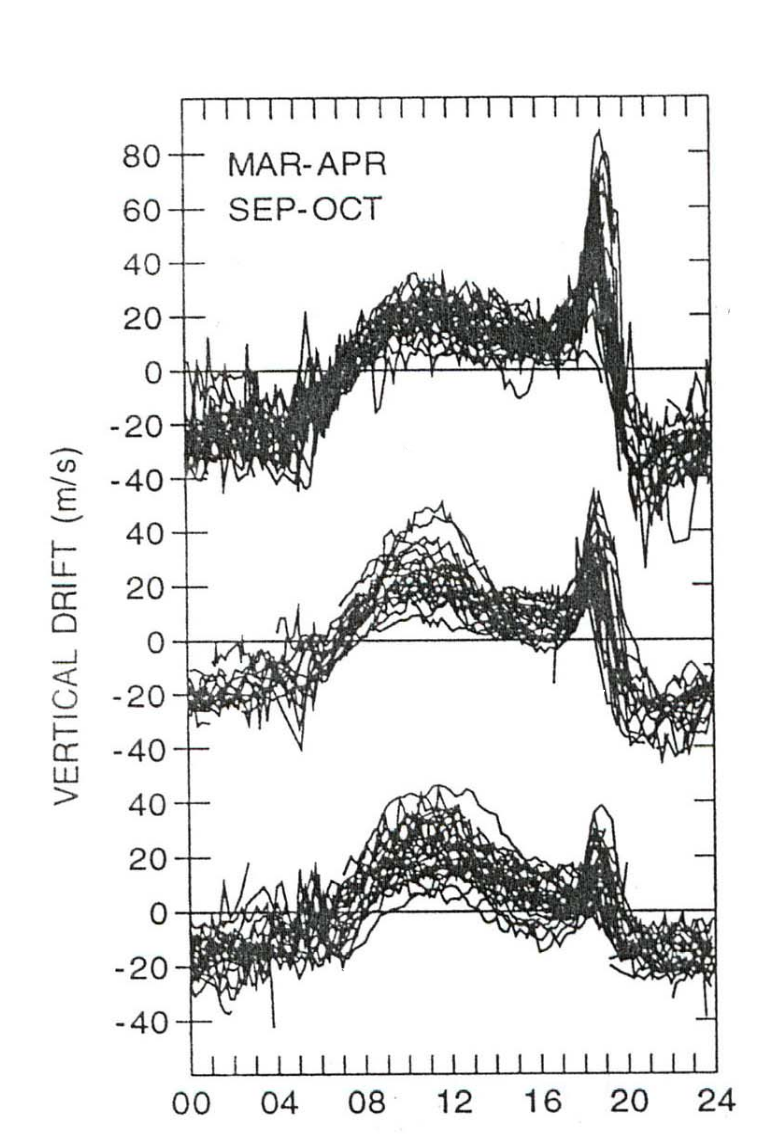


Jicamarca data

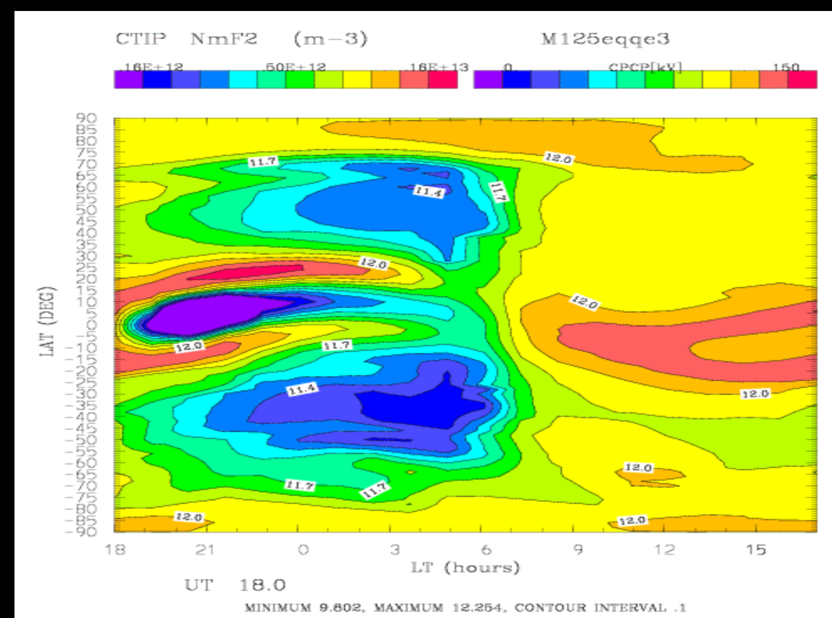
Scherliess and Fejer

Electrodynamics has strong control of low latitude ionosphere

- important to understand source of variability in the vertical plasma drift

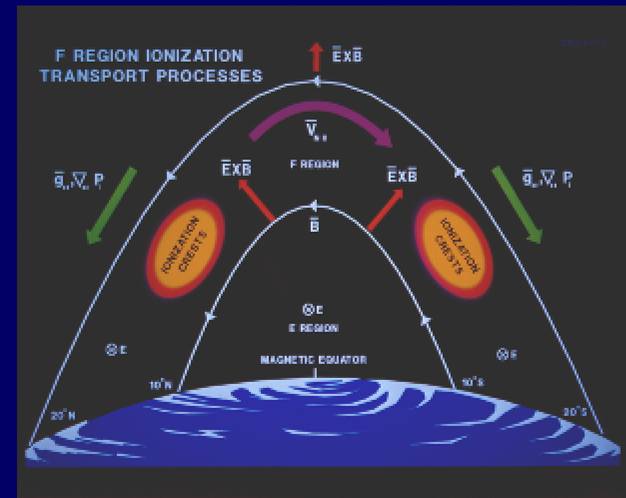


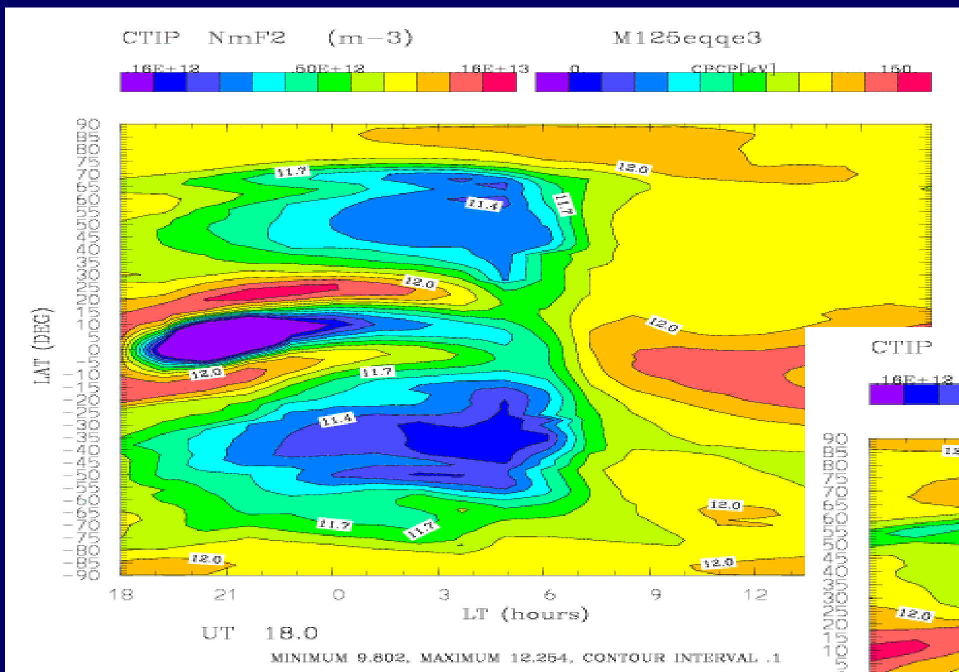
Jicamarca data
Scherliess and Fejer

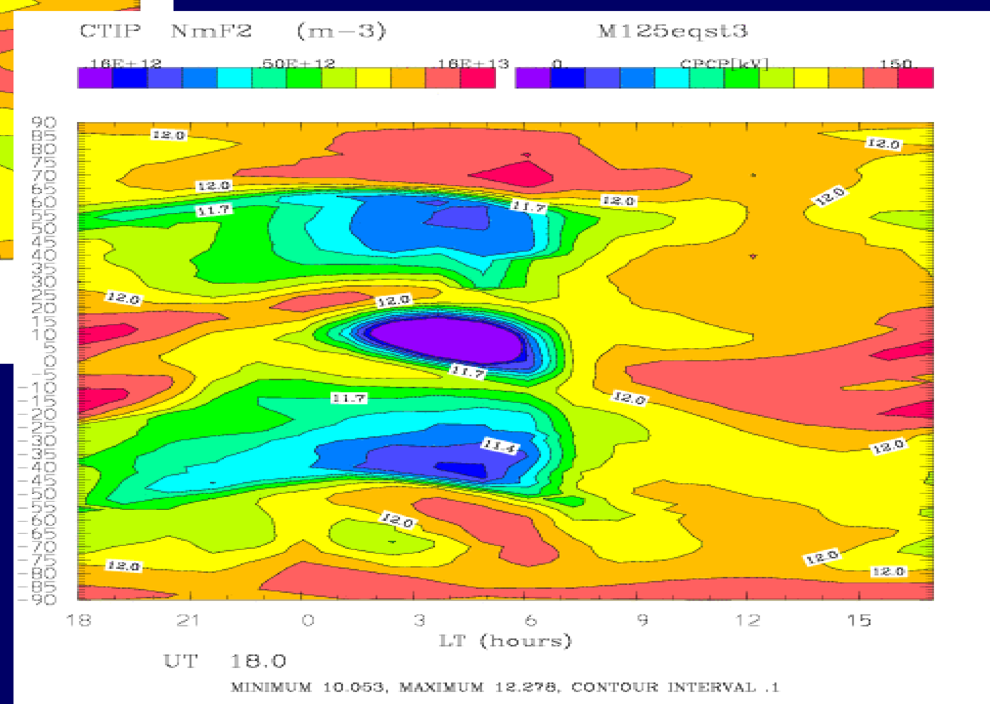


NmF2

Storm-time changes at mid and low latitudes

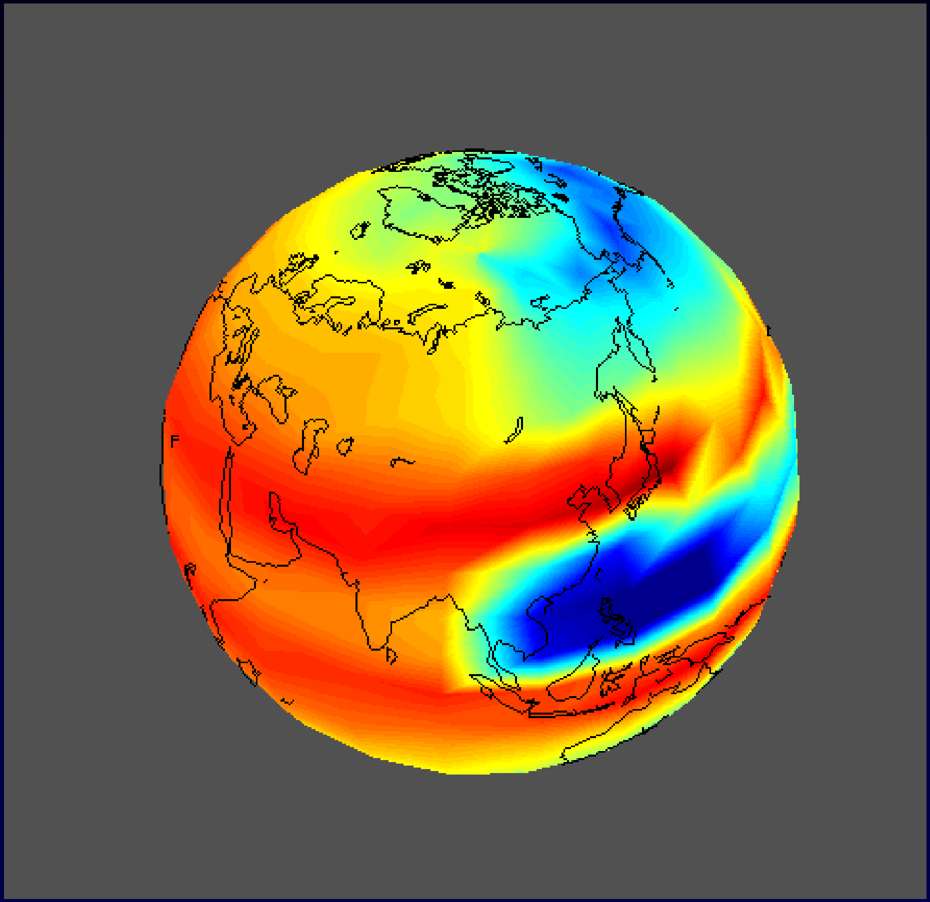






CTIPe physical model

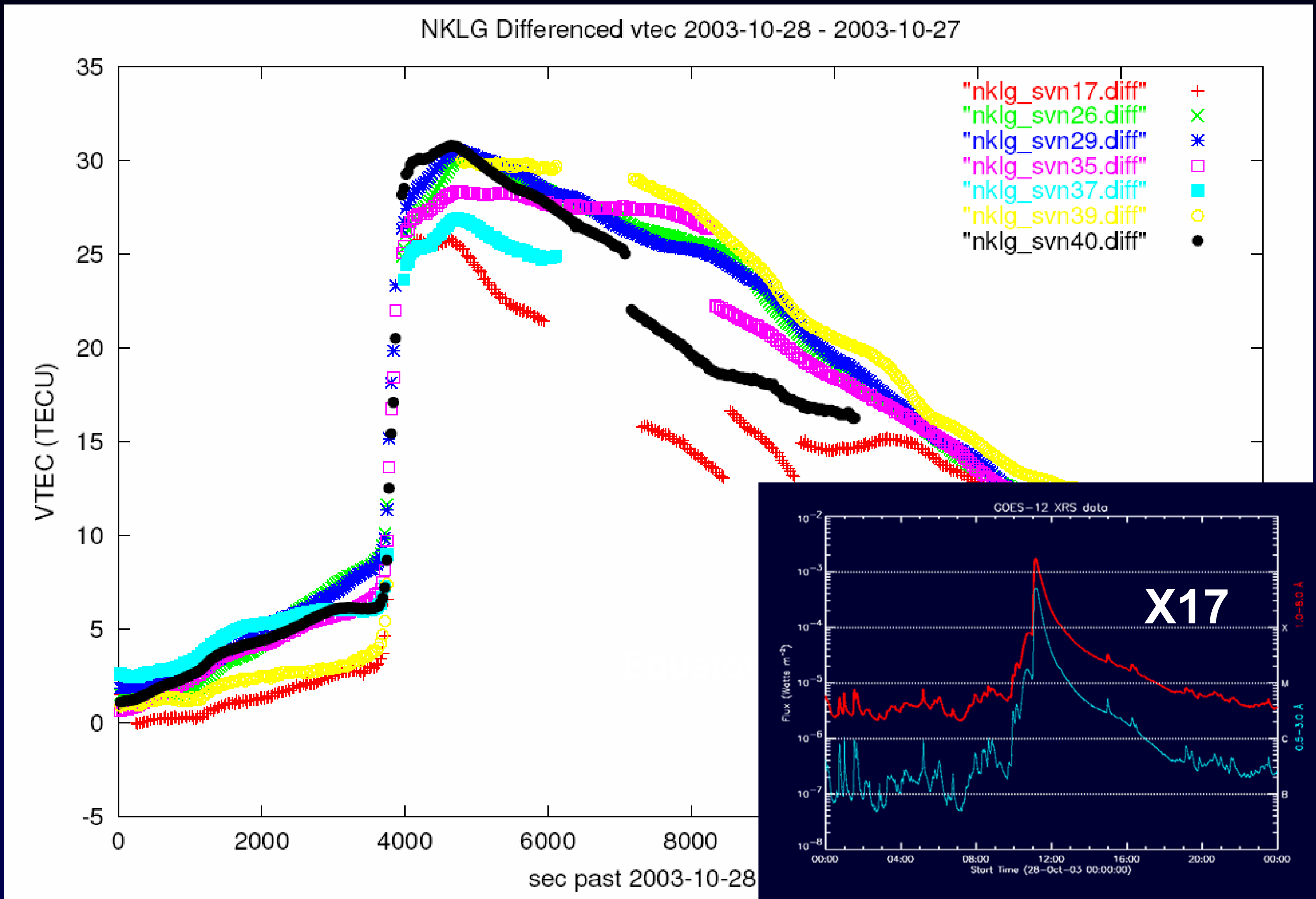
Modeling the global ionosphere:



- and its response to geomagnetic storms

ITSP target: the mid and low latitude storm response

TEC GPS Differential Phase measurements



Geomagnetic Storms

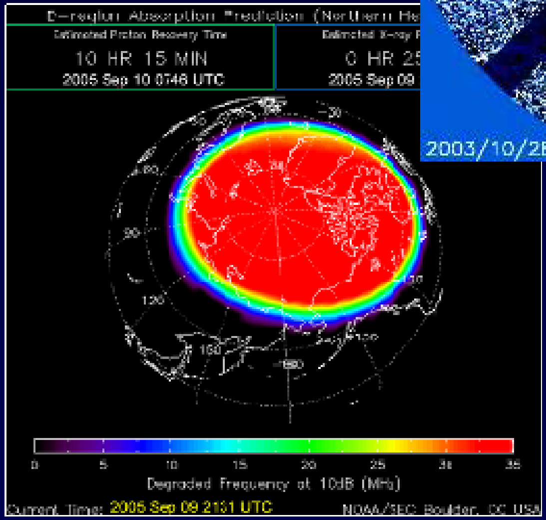
- Global
- Dynamic
- Affects power grids, aviation, satellites, geophysical surveys

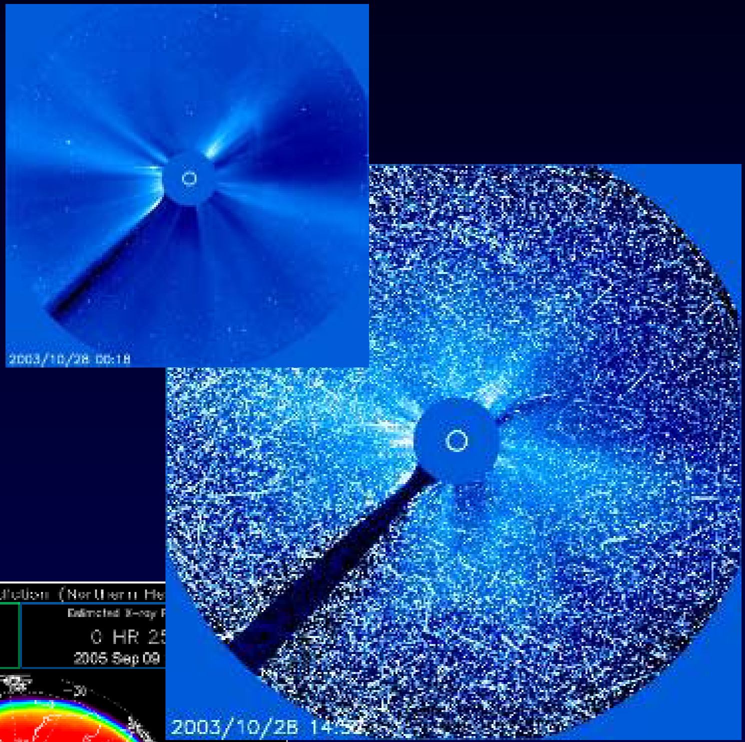
QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Movie courtesy of NASA

Solar Radiation Storms

- Larger than global
- Threatening
- Affects satellites, aviation, manned spaceflight

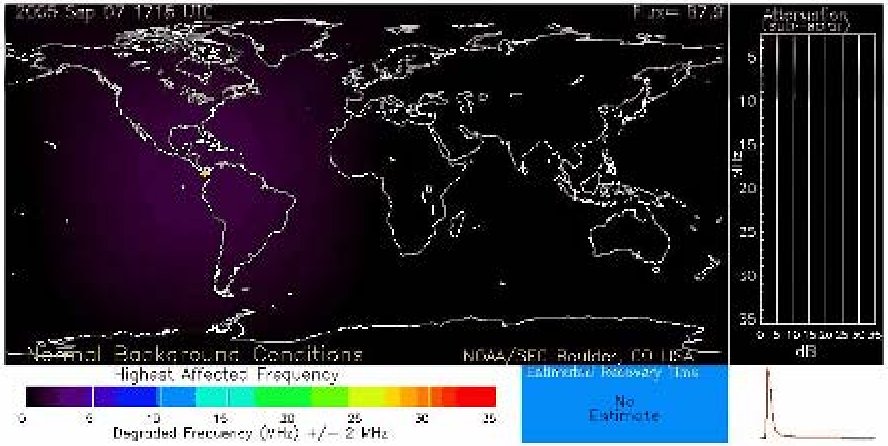


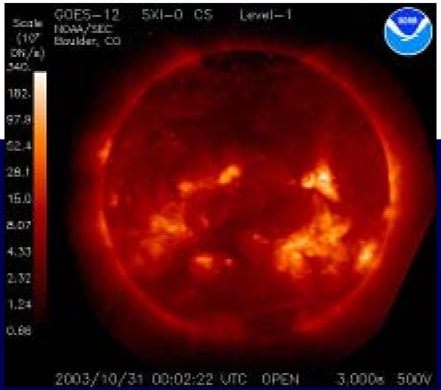


Courtesy of NASA

Radio Blackouts

- Dayside of Earth
- Speed of light
- Affects aviation, maritime, communications

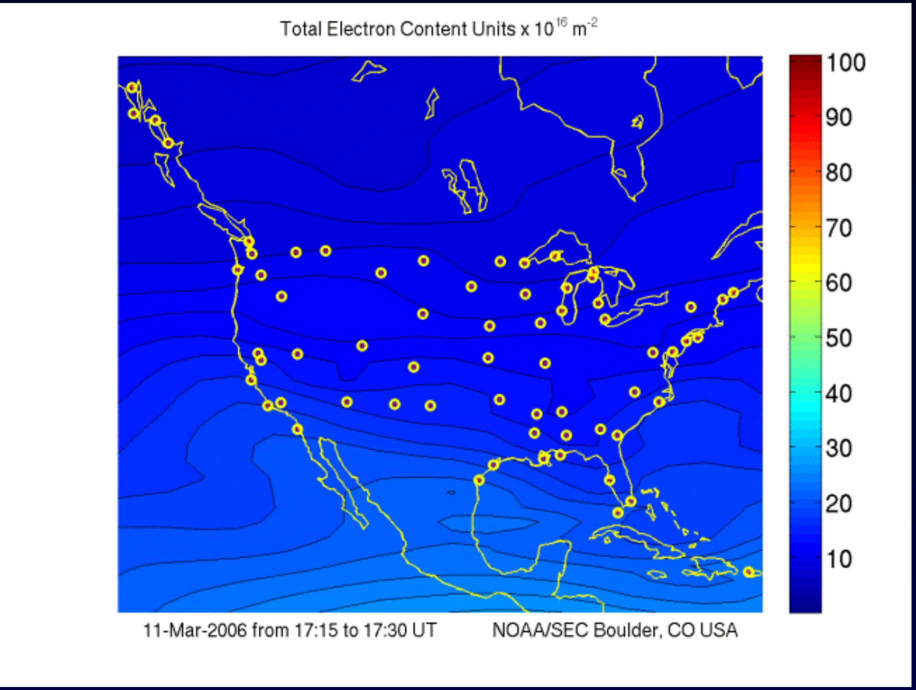




Recent improvements in response to user feedback

New Products:

Additional ASCII data files now available: uncertainty map, difference from 10-day average, EOFs and coefficients for reconstruction of full 3D electron density, daily zip file for easy download



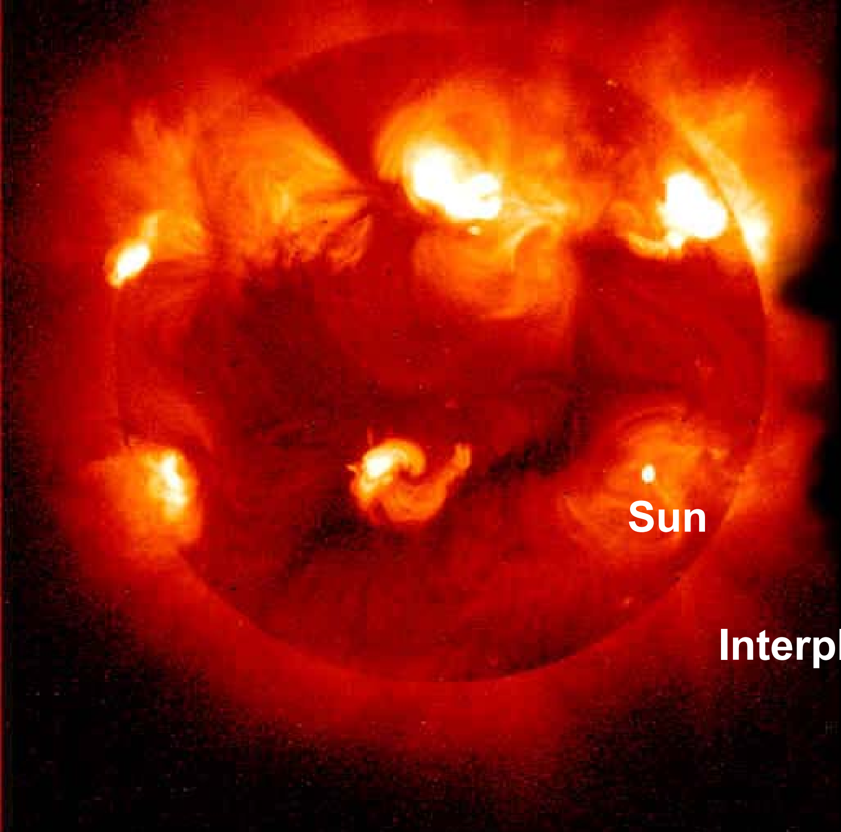
Additional features:

- **Parallel data stream established**
- **Number of stations increased**
- **Expand Kalman filter grid to extend slant maps to lower elevation**
- **Faster input data acquisition**
- **Rapid access to ASCII data files**
- **Larger images in png format**
- **Warning system for users**

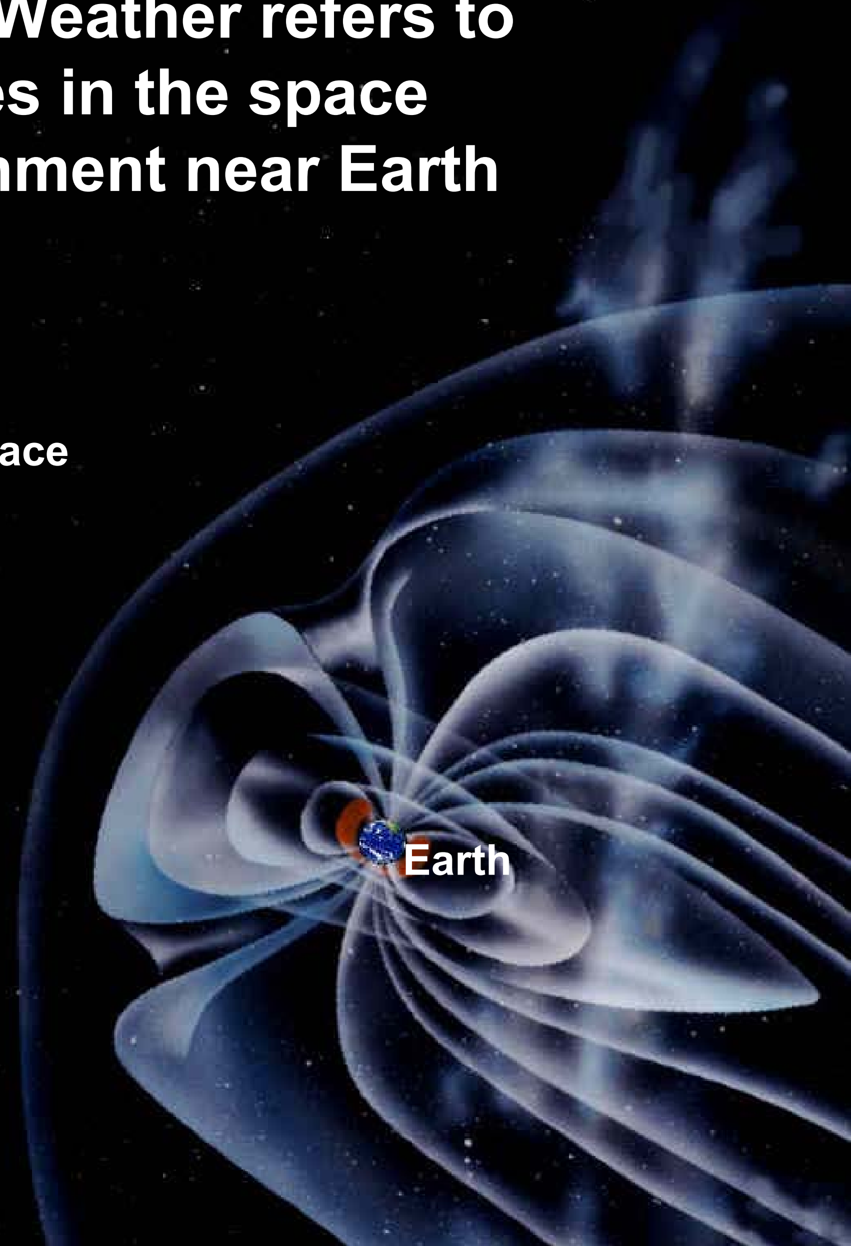
Space Weather:

What is it?

Space Weather refers to changes in the space environment near Earth



Interplanetary Space



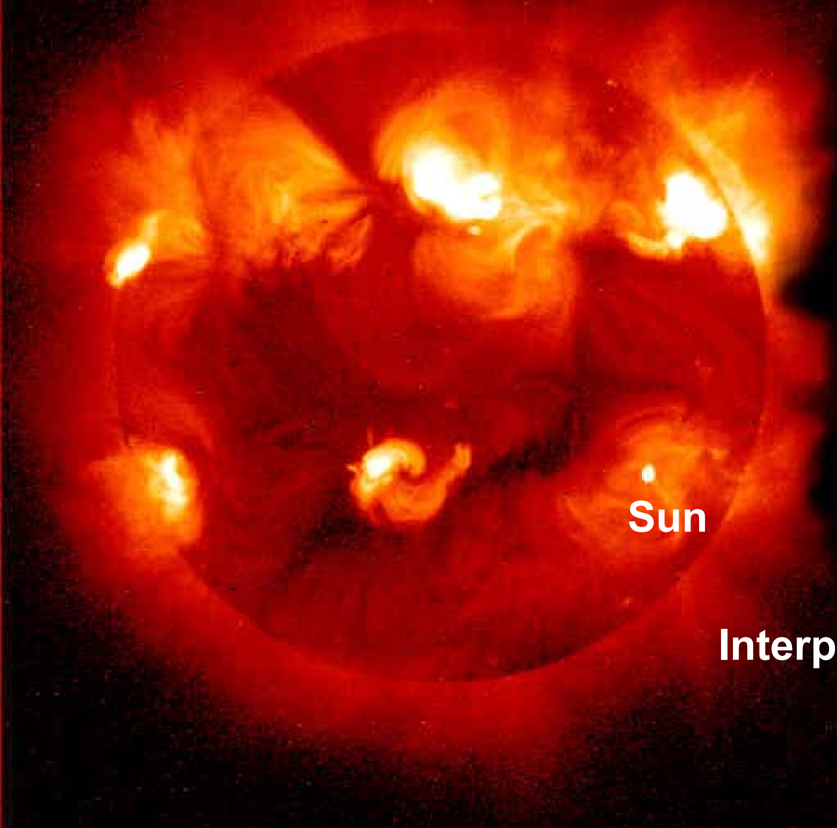
Interplanetary Space:

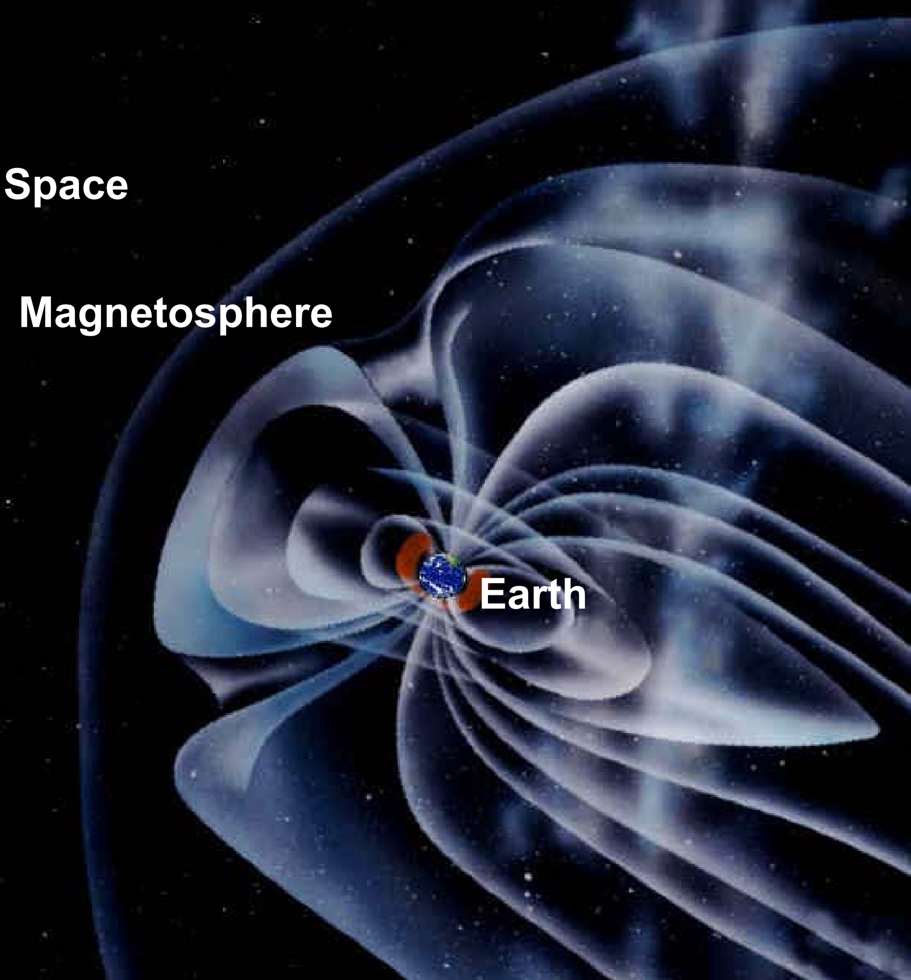
- Not quite a vacuum
- Solar Wind
    - Electrons and protons
    - Magnetic field
- Disturbances from the Sun make waves in the solar wind

Space Weather:

What is it?

Space Weather refers to changes in the space environment near Earth





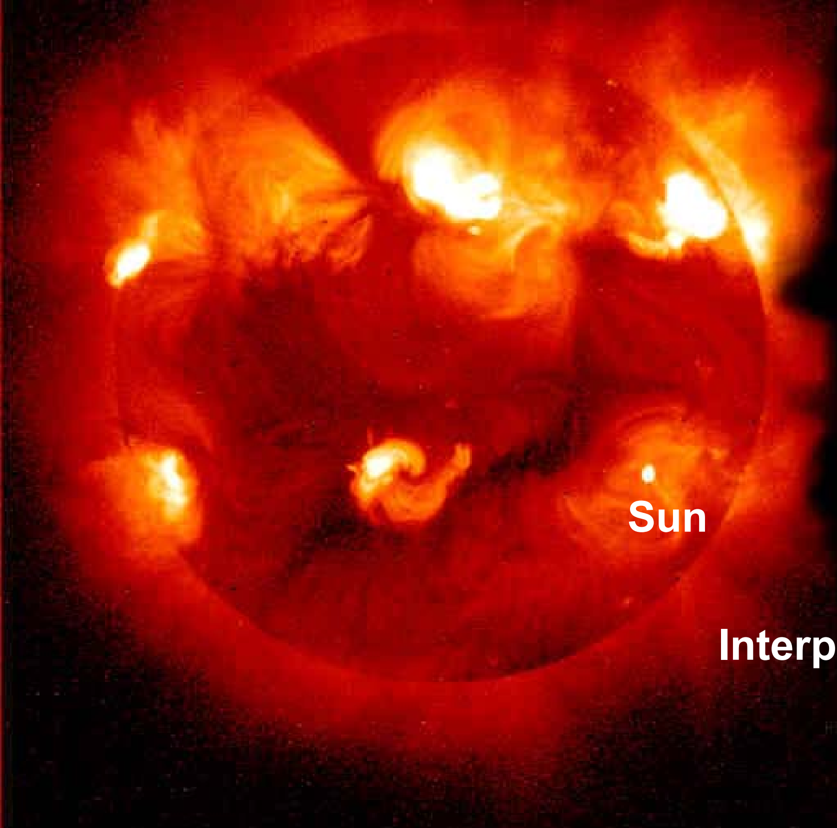
Magnetosphere:

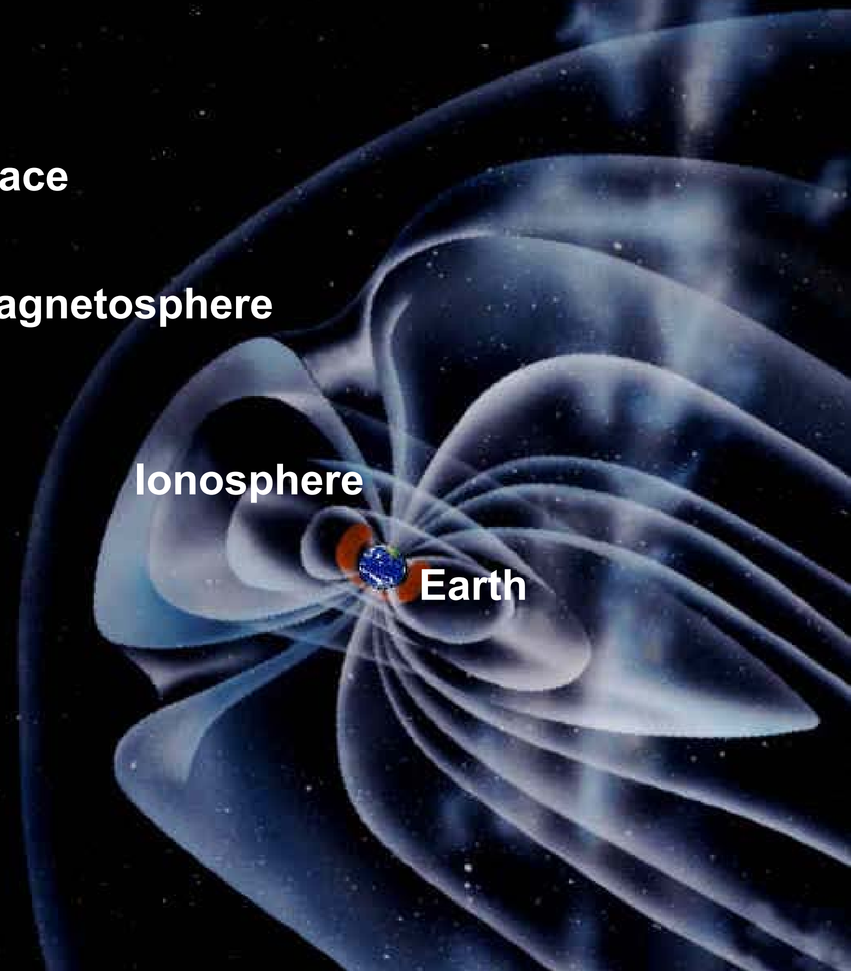
- Created by Earth’s magnetic field
- Deformed by the Solar Wind
  - Not Quite a Vacuum
    - Particles (electrons and protons) trapped on magnetic field lines

Space Weather:

What is it?

Space Weather refers to changes in the space environment near Earth





Ionosphere:

- Layer of electrons & ions at the top of the atmosphere (50 – 400 km & up)
- Formed when extreme ultraviolet light from the Sun hits Earth's Atmosphere
- Critical in the reflection and transmission of radio waves

Other Space Weather Terms

- **Geomagnetic Storm:** The disturbance in the near-Earth environment that can upset technological systems and fuel bright Aurorae.
- **Solar Wind:** The outward flow of electrons, protons, and magnetic field.
- **Solar Flare:** A small-scale eruption on the Sun that emits light (UV and x-rays) and particles (electrons and protons).
- **Coronal Mass Ejection (CME):** A disturbance in the solar wind caused by a large-scale eruption on the Sun.
- **Energetic Particles:** Electrons and protons that have been accelerated to high speeds.

The Sun
Solar Flares

- Rotates every 27 days
- Has an 11-year cycle of activity

A Solar Flare

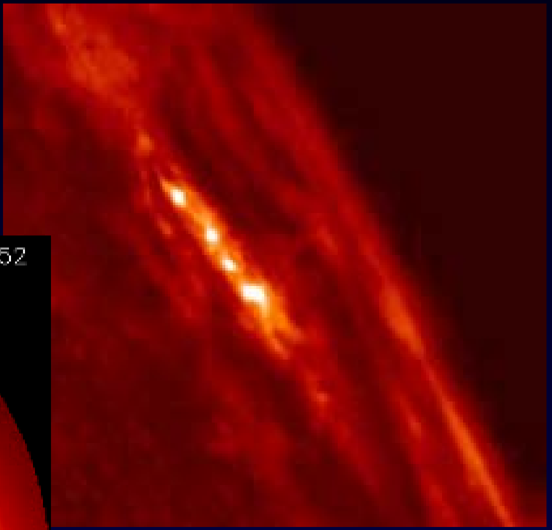
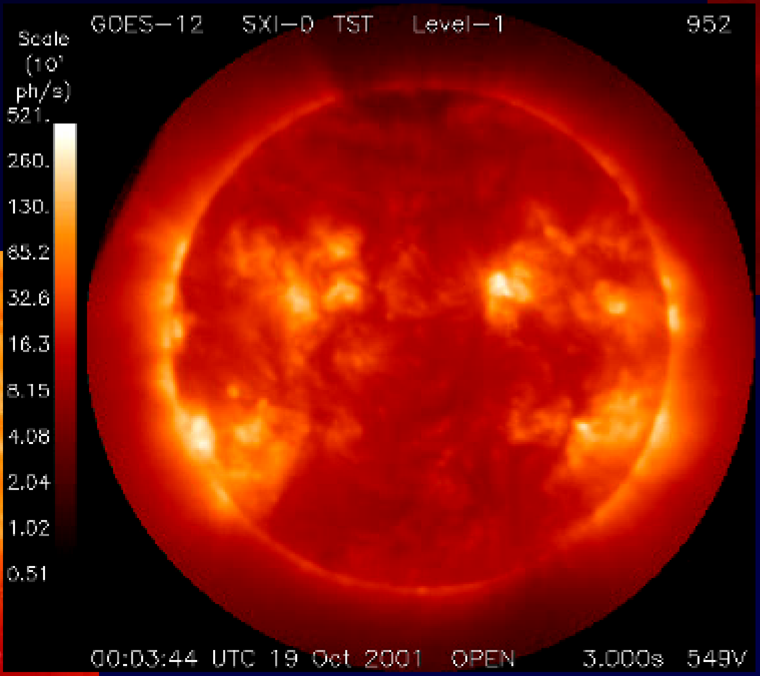


Image from NASA TRACE Satellite

The Sun in X-rays
From GOES 12



An Erupting Prominence

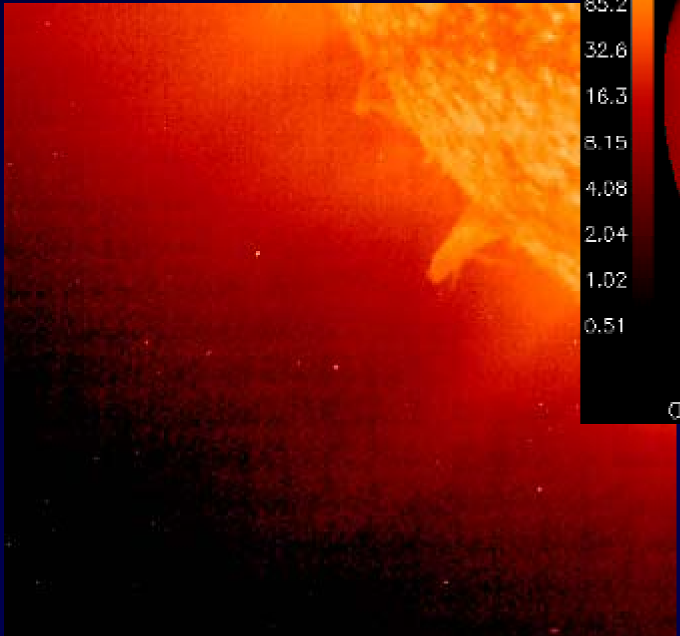


Image from NASA SOHO Satellite

CMEs in Interplanetary Space

- CMEs send out
  - Magnetic field and plasma
  - Energetic particles
  - Sometimes associated with flares

The CME disturbances propagate away from the Sun but their paths are modified by the background solar wind and the Sun's magnetic field

- Some of these disturbances reach Earth

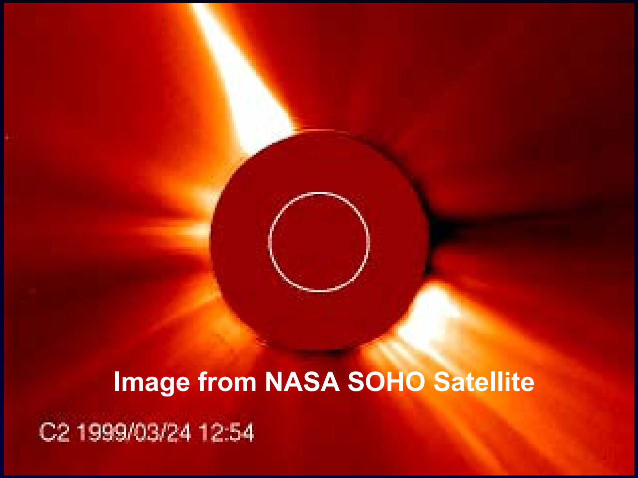


Image from NASA SOHO Satellite

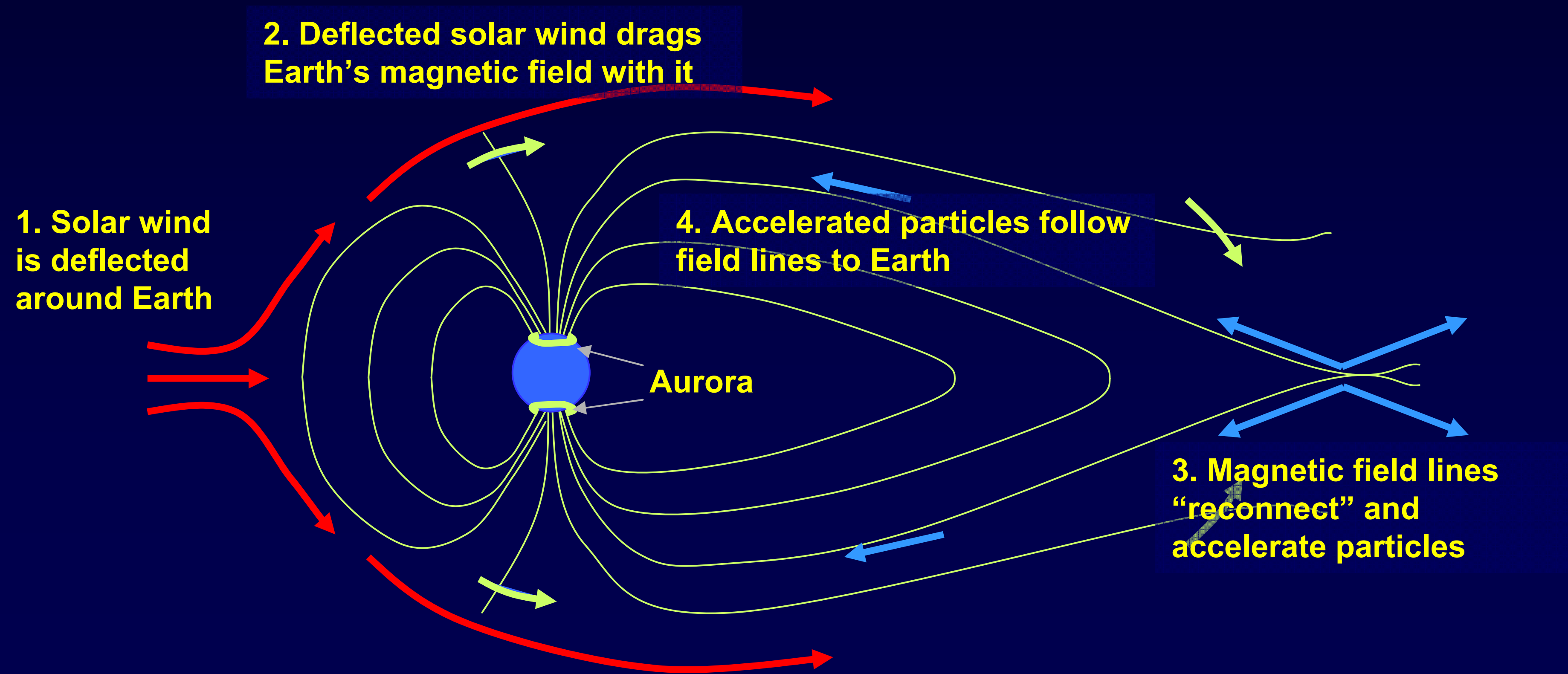
Image from NASA SOHO Satellite

Magnetosphere

What happens when a CME hits Earth?

1. Solar wind is deflected around Earth
2. Deflected solar wind drags Earth's magnetic field with it
3. Magnetic field lines "reconnect" and accelerate particles
4. Accelerated particles follow field lines to Earth

Aurora is produced when particles hit Earth's atmosphere



Ionosphere

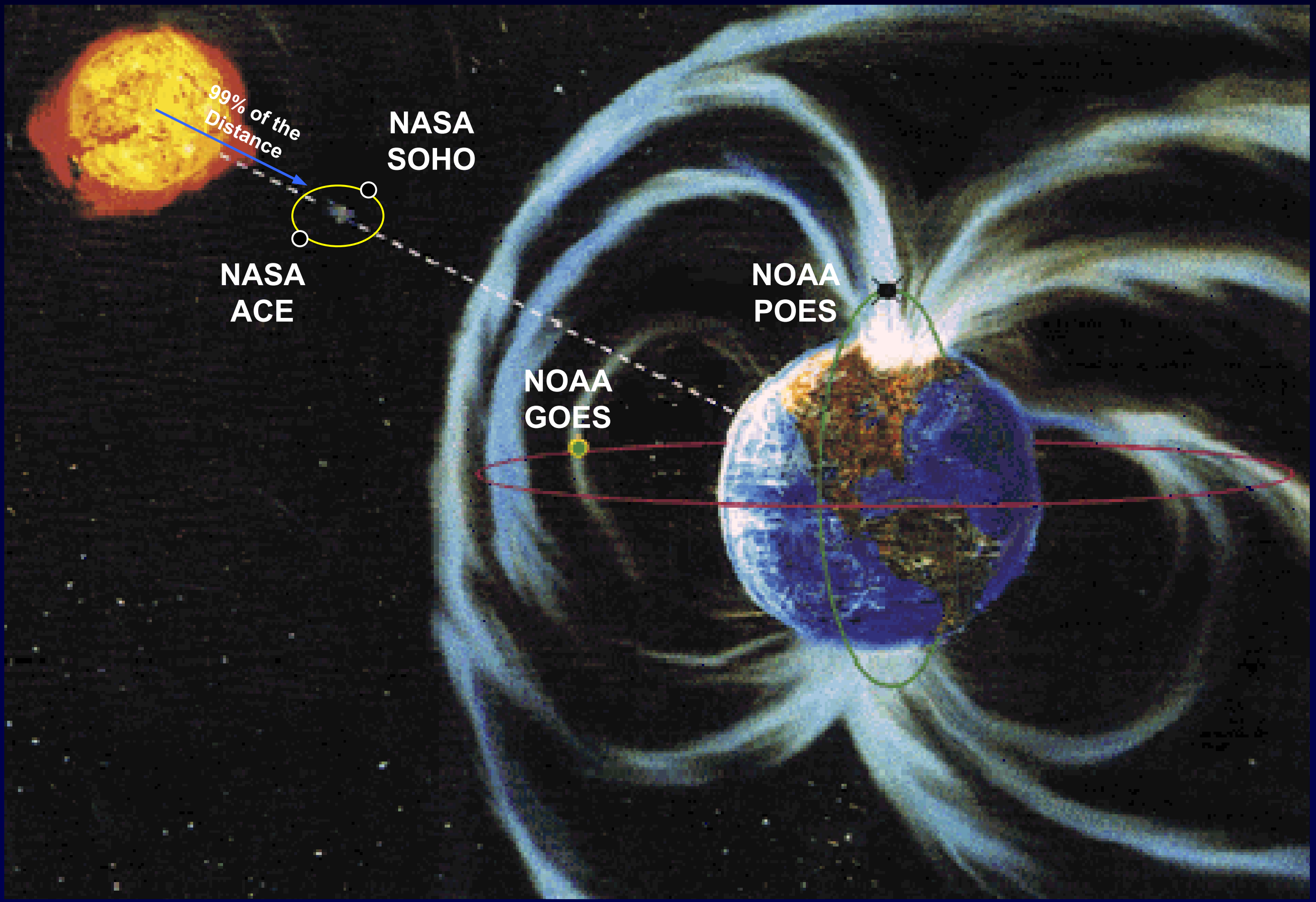
- The particles collide with the atmosphere and produce the Aurora and currents in the ionosphere.
- As geomagnetic activity increases, the Aurora gets brighter, more active, and moves equatorward.

Image from NASA IMAGE Satellite

Satellites For Making Space Weather Forecasts

- Events are observed on and near the Sun
- No in-situ measurements until the particles or CMEs are 99% of the way to Earth
- This provides only 30 minutes lead time for CMEs and no lead time for other events

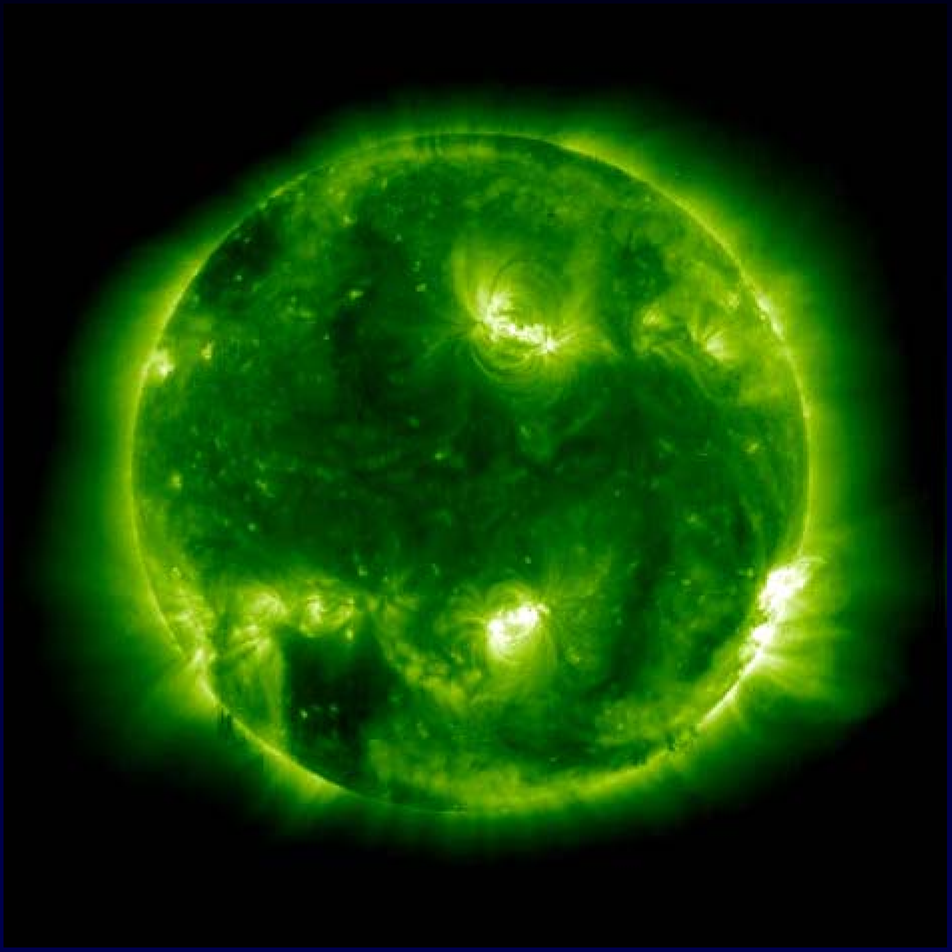
- NOAA Satellites
  - Monitor the Sun
  - Measure the near-Earth environment
- NASA Satellites
  - Monitor the Sun
  - Measure the interplanetary environment



Space Weather Storms

Timing and Consequences

- A Flare and/or CME erupt on the Sun
- 8 minutes later: First blast of EUV and X-Ray light increases the ionospheric density
  - Radio (HF) communications are lost
- 30 to 1000 minutes later: Energetic Particles arrive
  - Astronauts are impacted
  - Satellites are impacted
  - Polar flights are impacted
- 1 to 4 days later: CME passes and energizes the magnetosphere and ionosphere
  - Electric Power is affected
  - Navigation Systems are affected
  - Radio Communications are affected



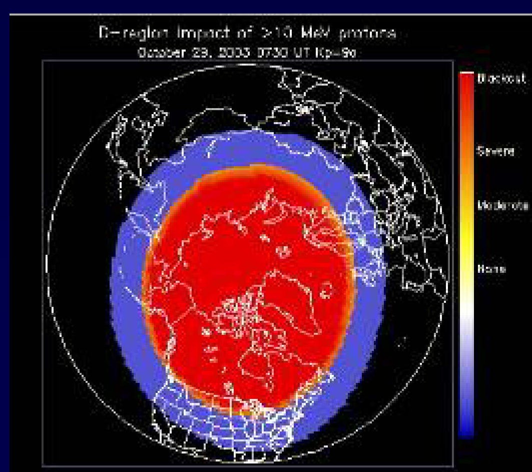
Movie from NASA SOHO Satellite

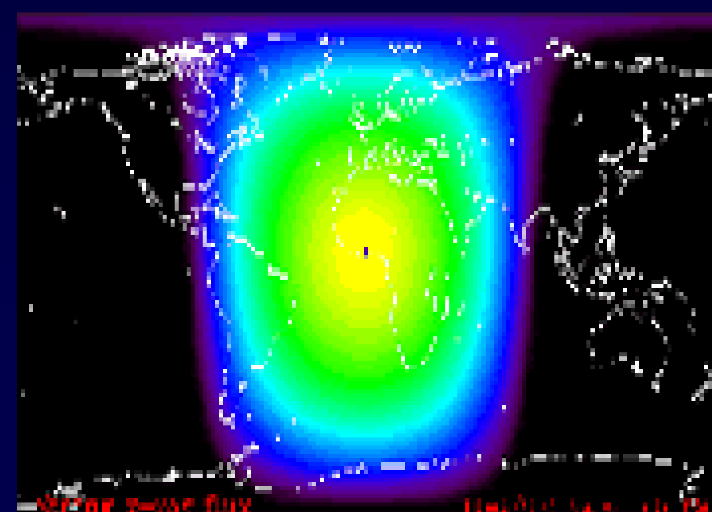
Airline Communications

Solar flare x-rays cause HF outages on the dayside.

Energetic particles create lengthy HF outages in the polar regions.

Polar cap affected, total loss of HF.



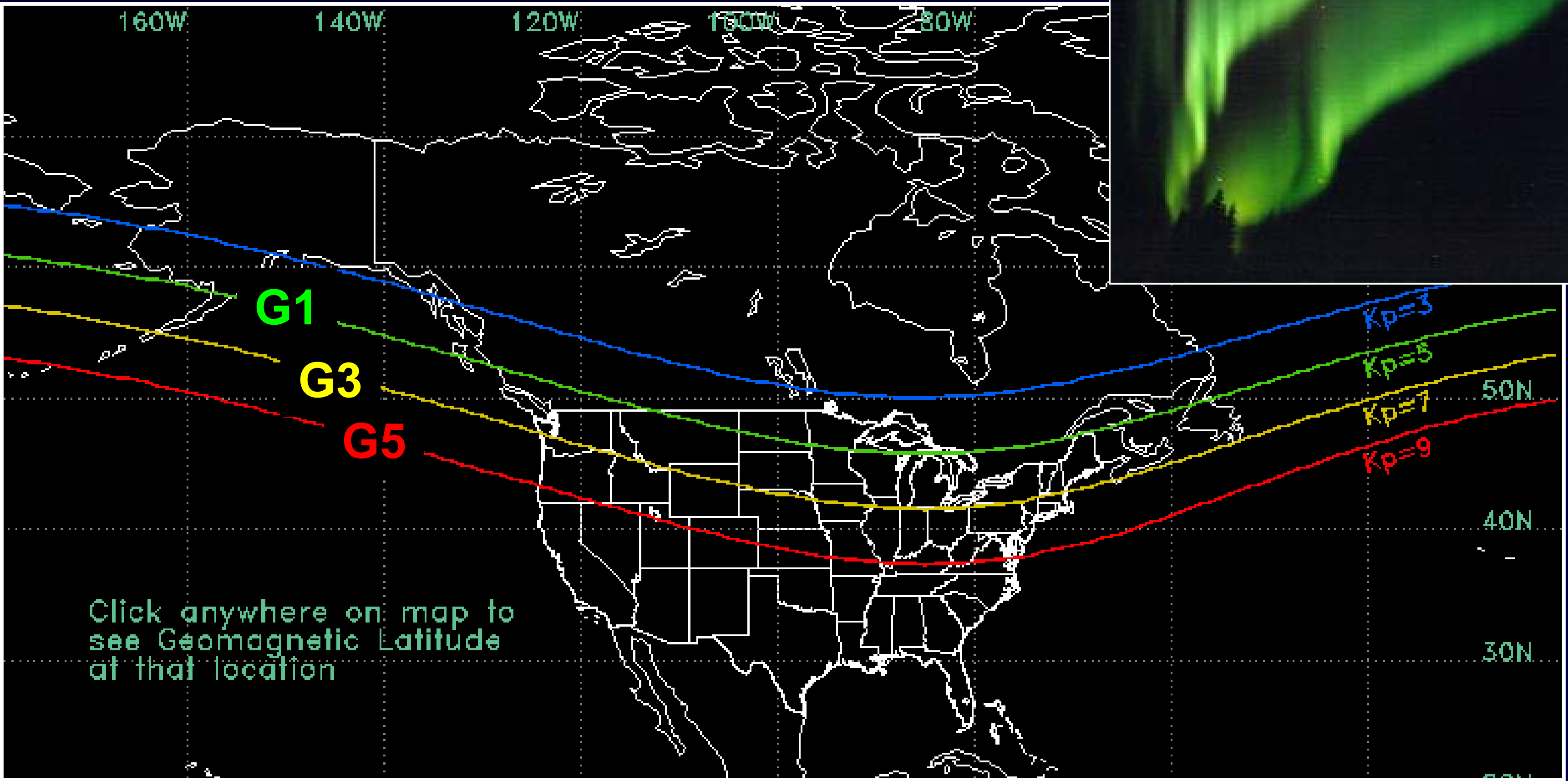


Geomagnetic Storm Effects

Aurora

- Intensity and location depend on strength of storm
- Best time to view is around midnight
- No guarantee that aurora will occur

Photo by Jan Curtis, http://www.geo.mtu.edu/weather/aurora



Customers for Ionospheric Information

- **High Frequency (HF) Communication**
  - ground-to-ground or air-to-ground communication
  - establish accurate maximum useable frequencies
  - radio wave absorption
- **Positioning and Navigation**
  - single frequency GPS positioning
  - dual frequency GPS, DGPS, RTK, rapid integer ambiguity resolution
- **Satellite Communication**
  - specification and forecast of scintillation activity
- **Situational Awareness**
  - Depressed maximum useable frequencies
  - Steep horizontal gradients
  - Unusual propagation paths
  - Larger positioning errors
  - High probability of loss of radio signals

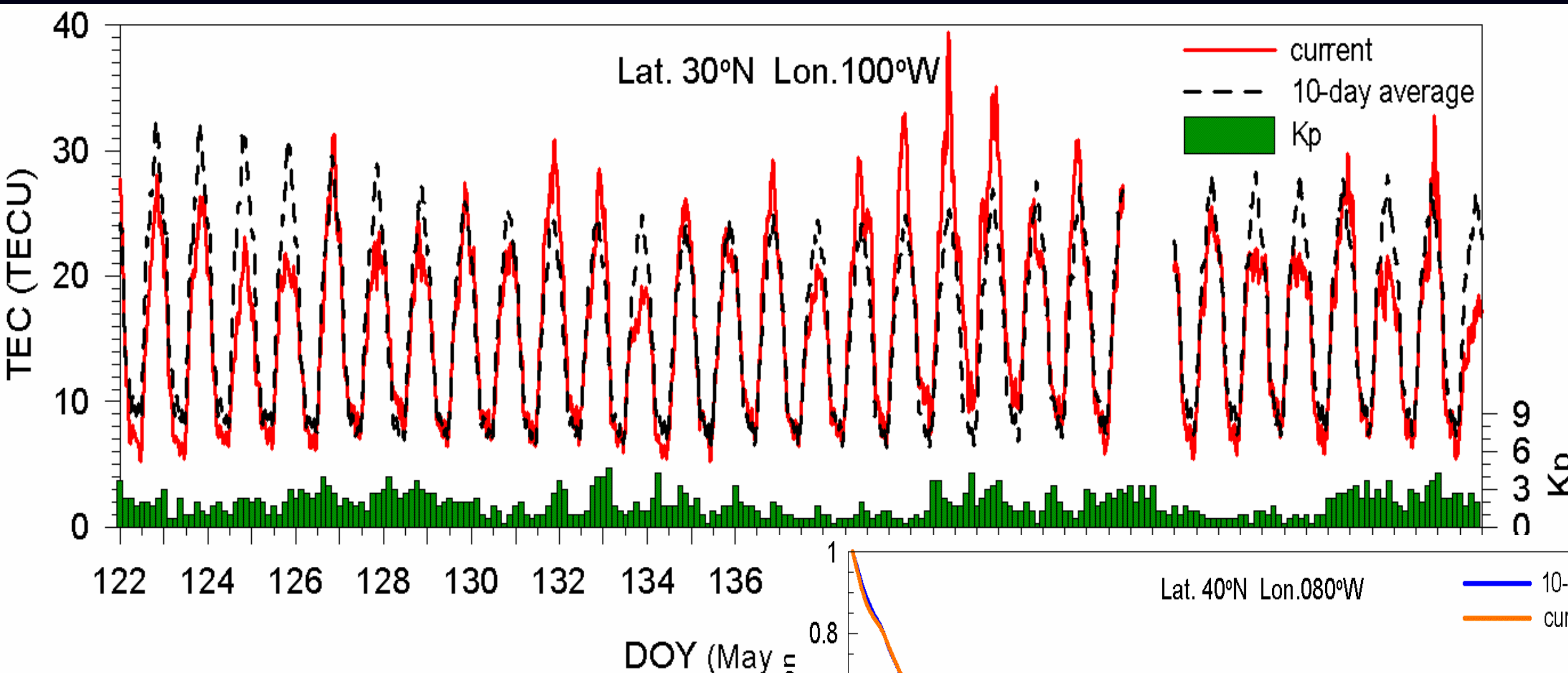
US-TEC Validation Summary

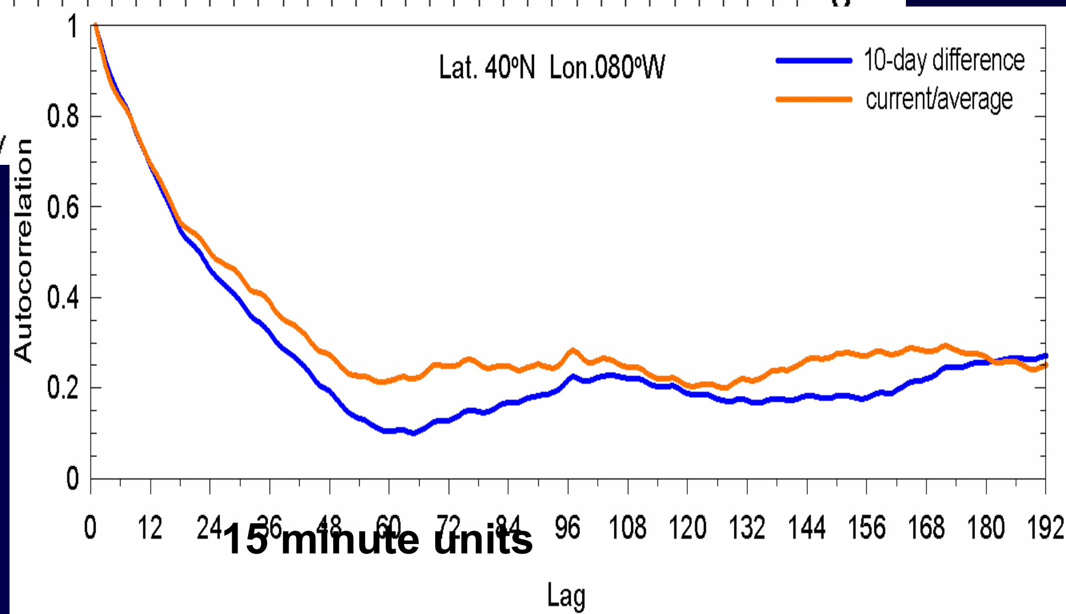
Differential TEC:
Slant = 2.4 TEC units
Vertical = 1.7 TEC units

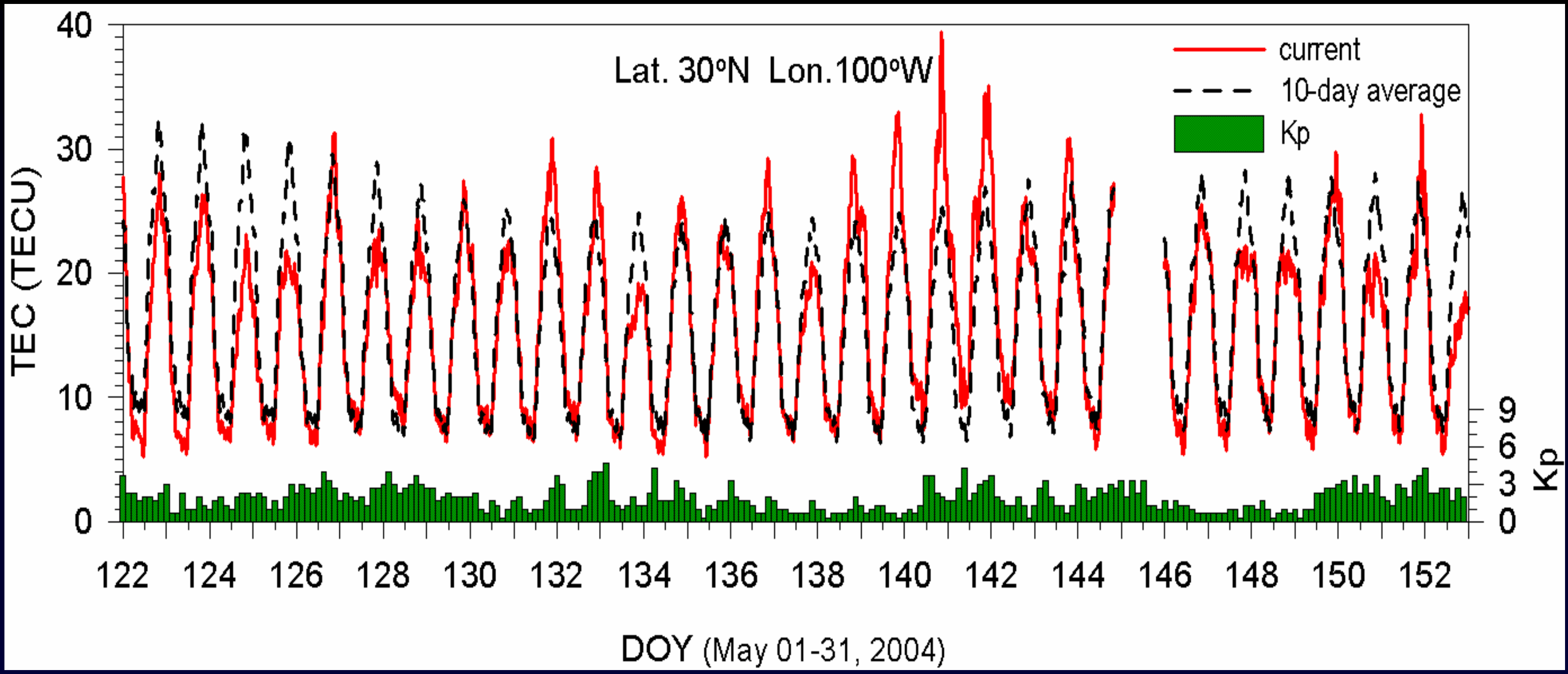
"Absolute" FORTE ray tracing:
Slant = 2.7 TEC units
Vertical = 1.9 TEC units

- **Estimated US-TEC slant path total electron content uncertainty < 3 TEC units (equivalent to about 45 cm of signal delay at L1 frequencies)**
- **Estimate US-TEC vertical total electron content uncertainty < 2 TEC units (equivalent to about 30 cm of signal delay at L1 frequencies)**

The challenge in forecasting the ionosphere and total electron content






Lat. 30°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
40
30
20
10
0
9
6
3
0
Kp
122
124
126
128
130
132
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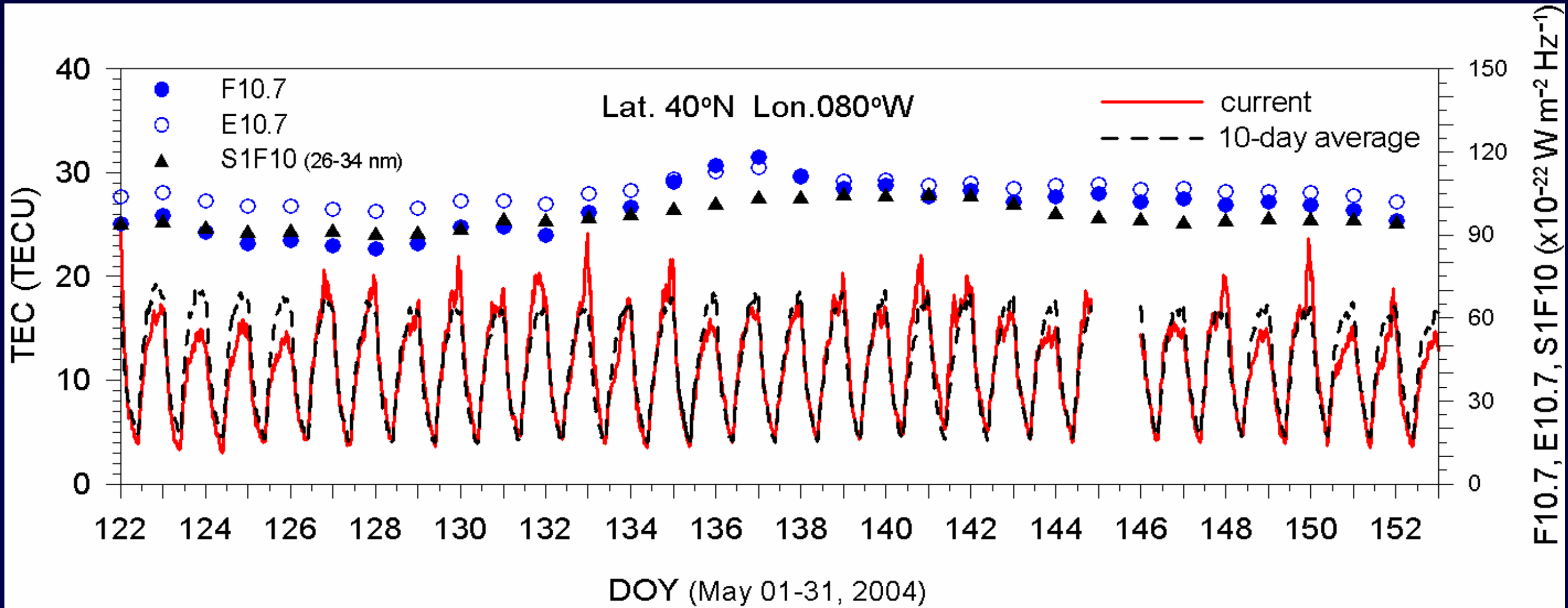
136
138
140
142
144
146
148
150
152
DOY (May 01-31, 2004)


F10.7
E10.7
S1F10 (26-34 nm)
Lat. 40°N Lon.080°W
current
10-day average
TEC (TECU)
40
30
20
10
0
150
120
90
60
30
0
F10.7, E10.7, S1F10 (x10^-22 W m^-2 Hz^-1)
122
124
126
128
130
132
134
136
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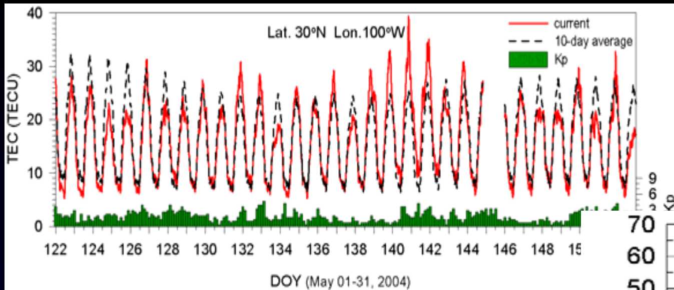
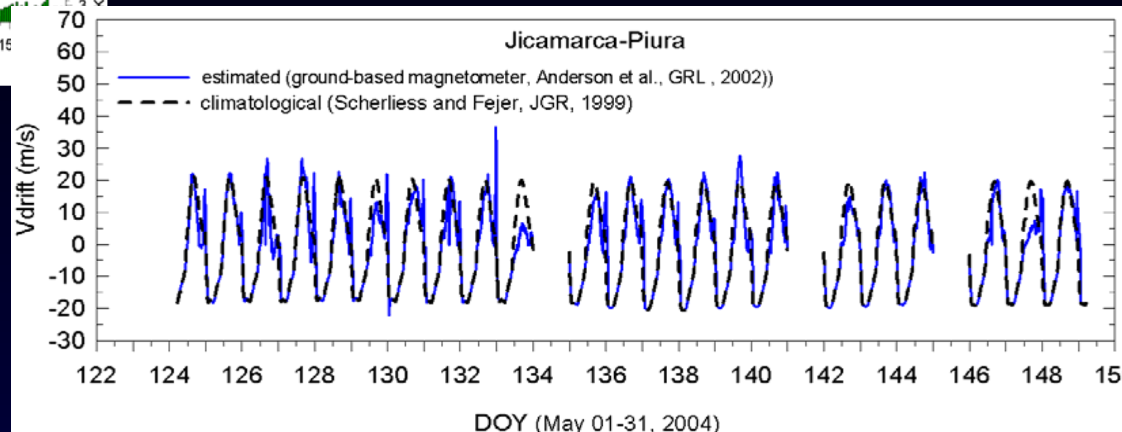
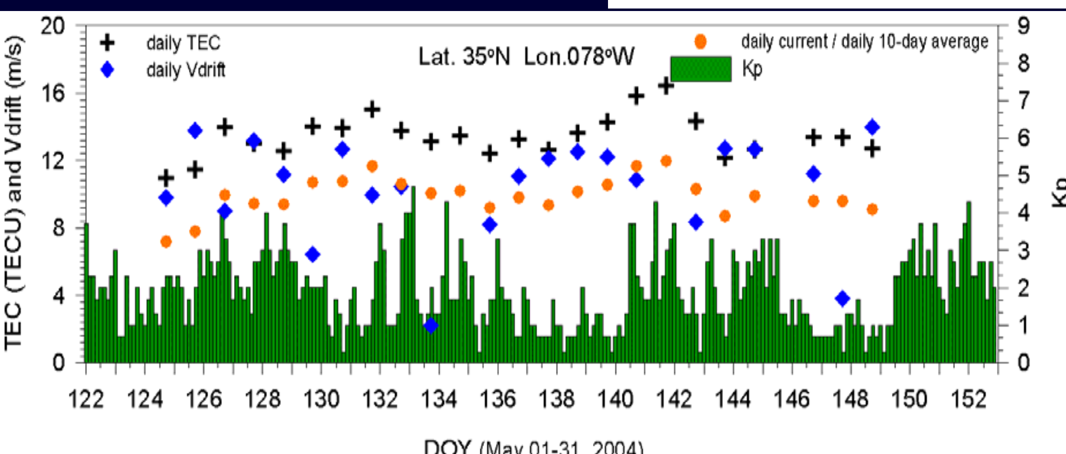
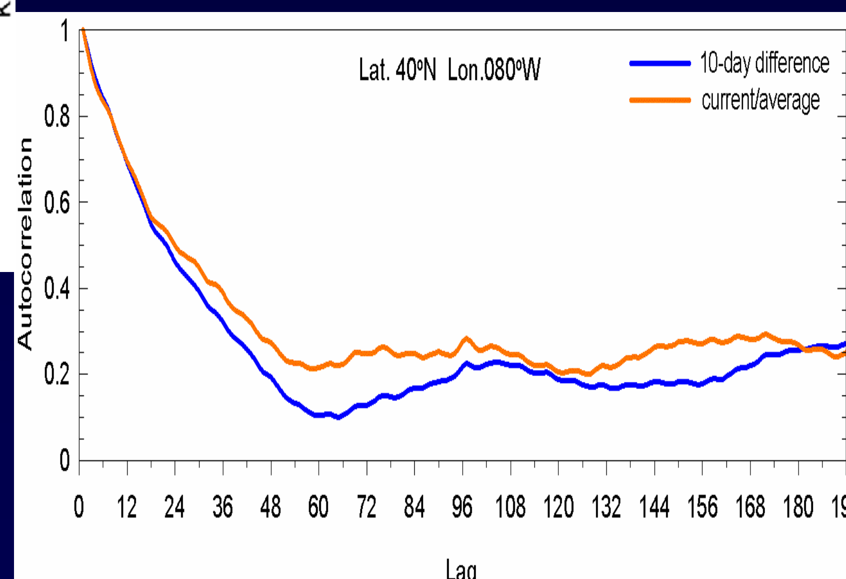
144
146
148
150
152
DOY (May 01-31, 2004)


Lat. 30°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
DOY (May 01-31, 2004)

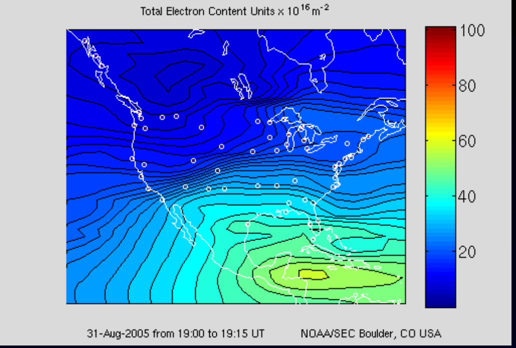

Jicamarca-Piura
estimated (ground-based magnetometer, Anderson et al., GRL , 2002))
climatological (Scherliess and Fejer, JGR, 1999)
Vdrift (m/s)
DOY (May 01-31, 2004)


daily TEC
daily Vdrift
Lat. 35°N Lon.078°W
daily current / daily 10-day average
Kp
TEC (TECU) and Vdrift (m/s)
DOY (May 01-31, 2004)


Lat. 40°N Lon.080°W
10-day difference
current/average
Autocorrelation
Lag

Forecasts

- Three types
  - Short term (event-driven alerts, warnings, watches – minutes to hours)
  - Mid term (routinely made daily – 1-3 days ahead)
  - Long term (routinely made weekly -- weeks to months ahead)
- Use satellite and ground based space weather data
- Use model outputs, i.e., shock model, protons, ….
- Human oversight and experience



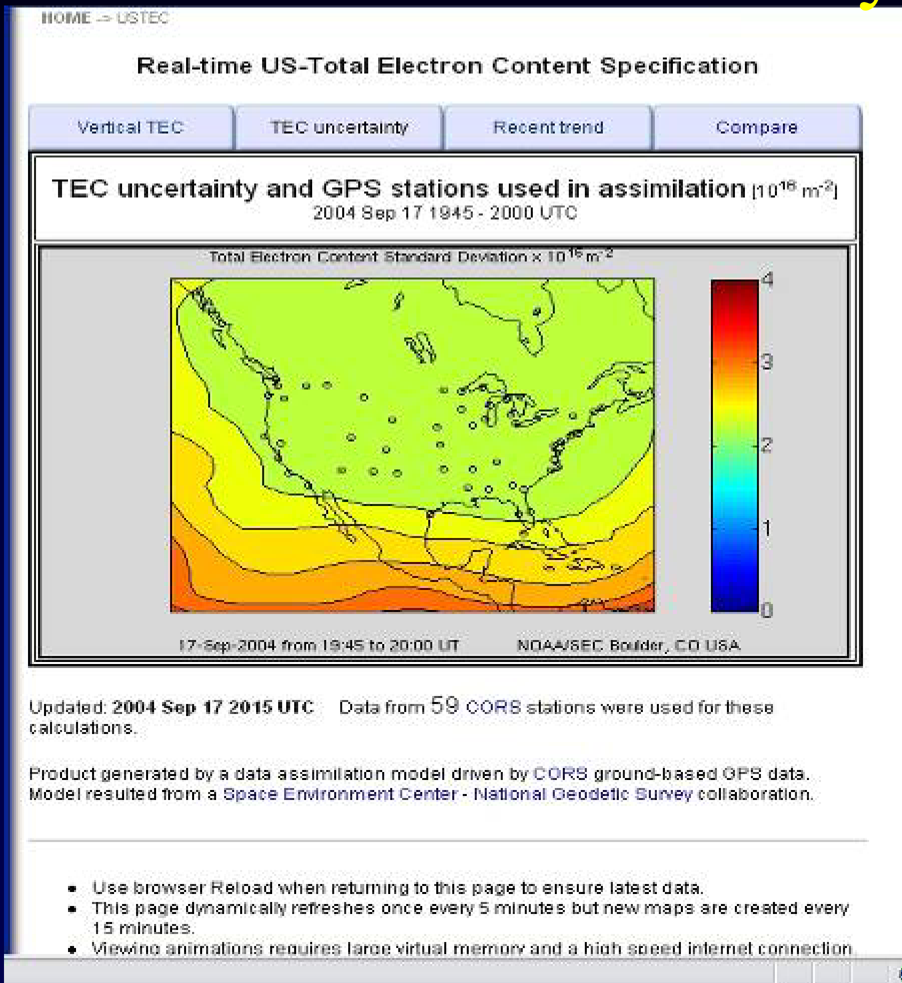
Product on Web page:
http://www.sec.noaa.gov/ustec

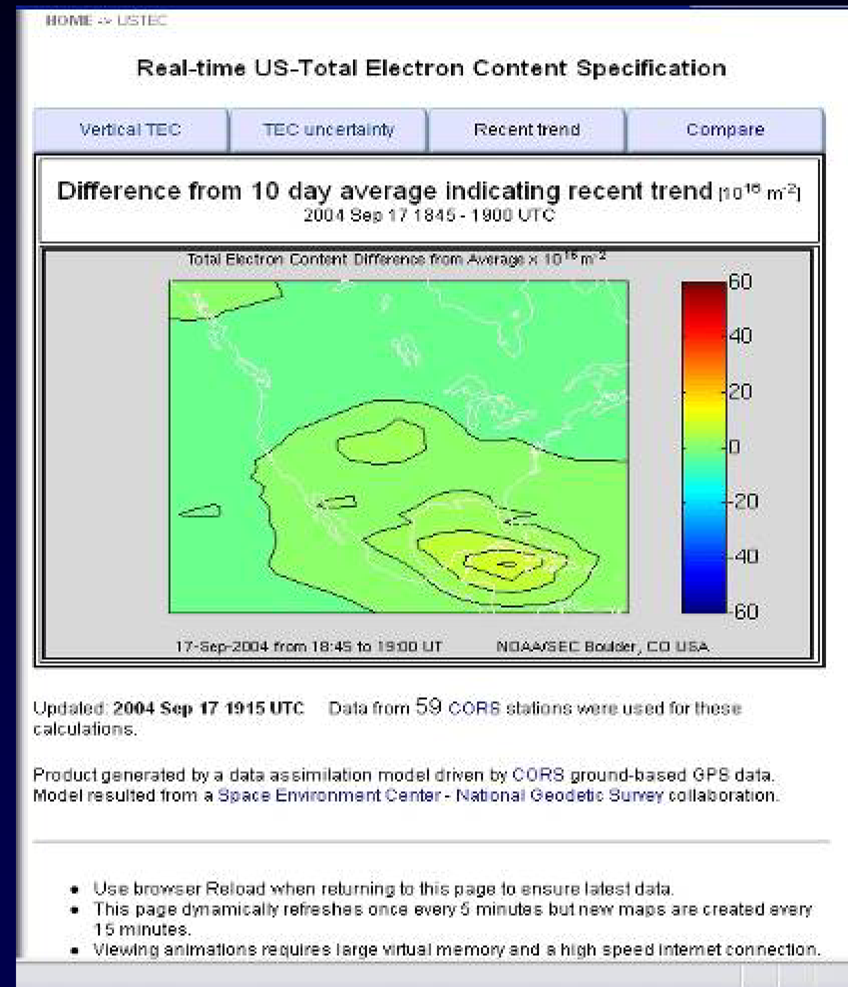
- **Vertical TEC map over CONUS updated every 15 minutes**
- **Estimated uncertainty in TEC**
- **Location of current data sites**
- **Difference from 10-day average to show recent trend**

- **Data files:**
  a) **vertical TEC**
  b) **slant path TEC for each GPS satellite in view**

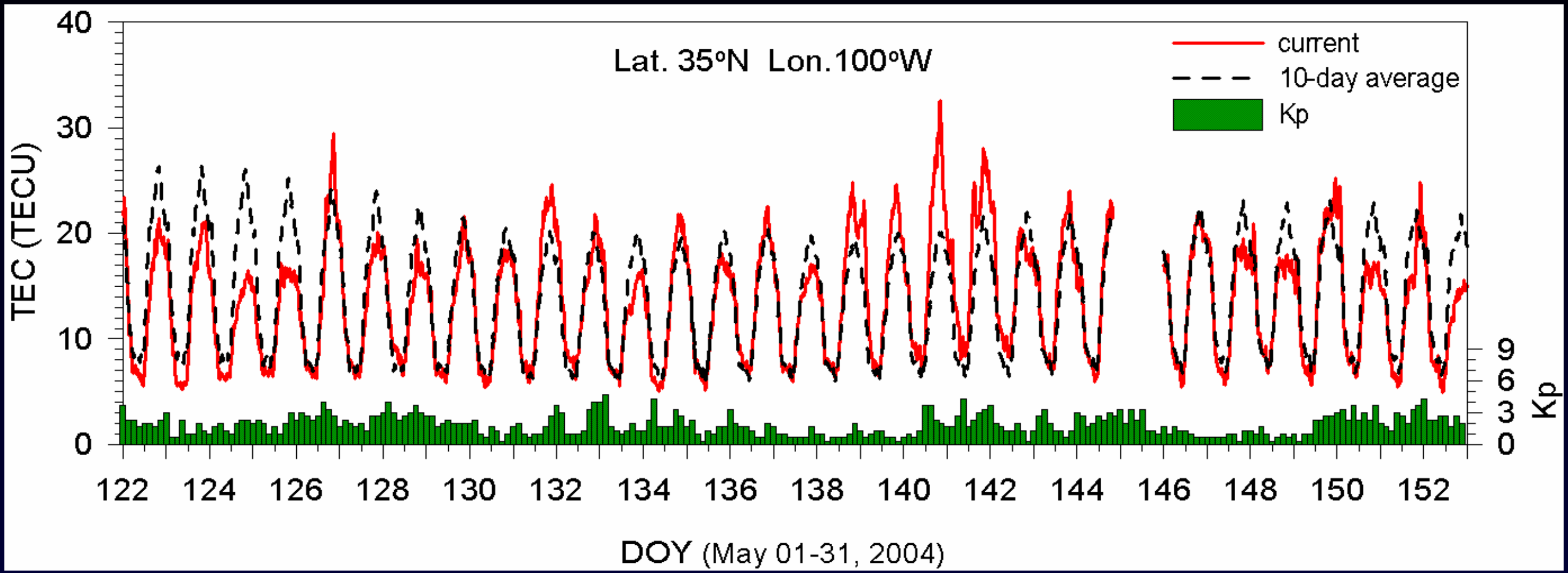
Supporting Products:

Estimated Uncertainty Recent Trend





URL: http://www.sec.noaa.gov/ustec


Lat. 35°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
0
10
20
30
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Kp
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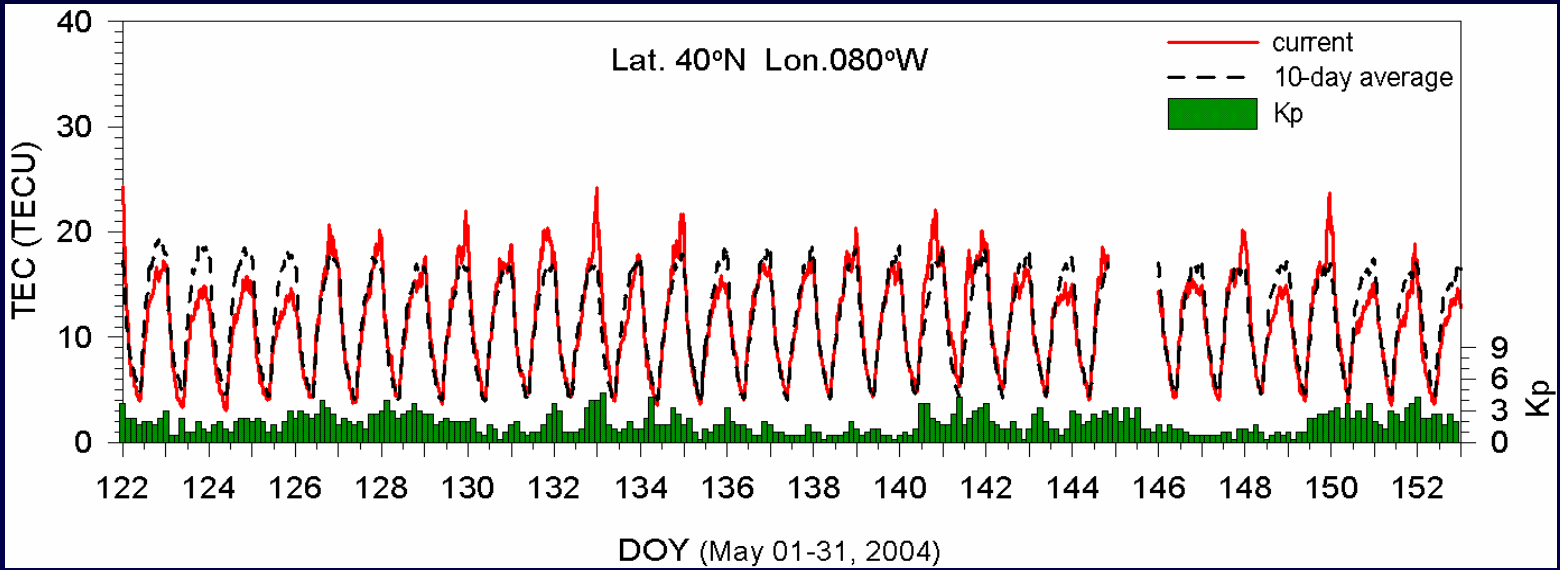
DOY (May 01-31, 2004)


Lat. 40°N Lon.080°W
current
10-day average
Kp
TEC (TECU)
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Kp
0
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6
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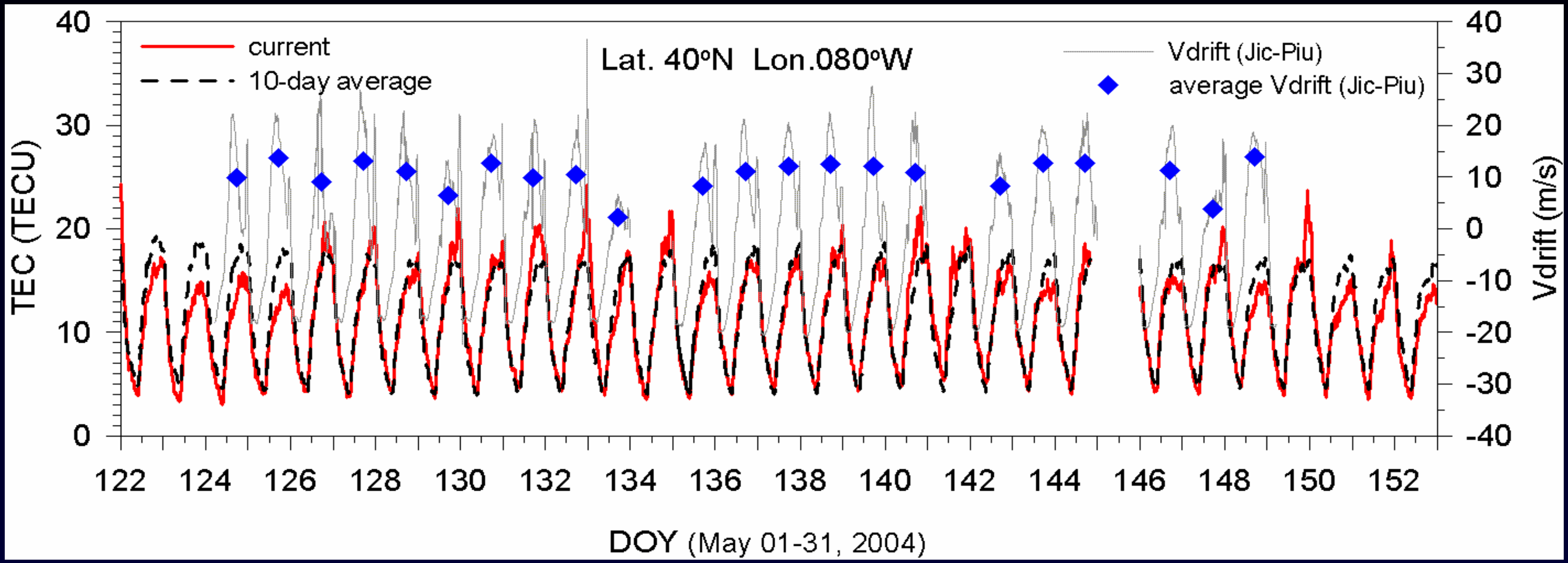
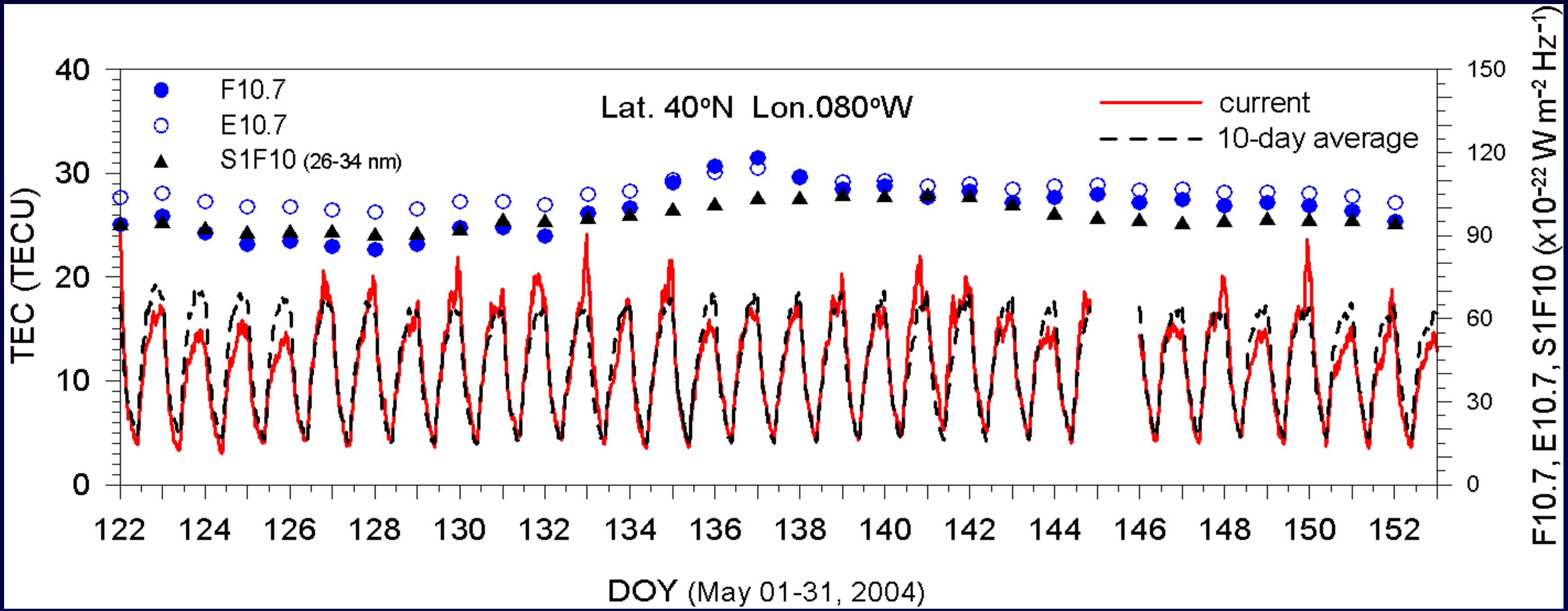
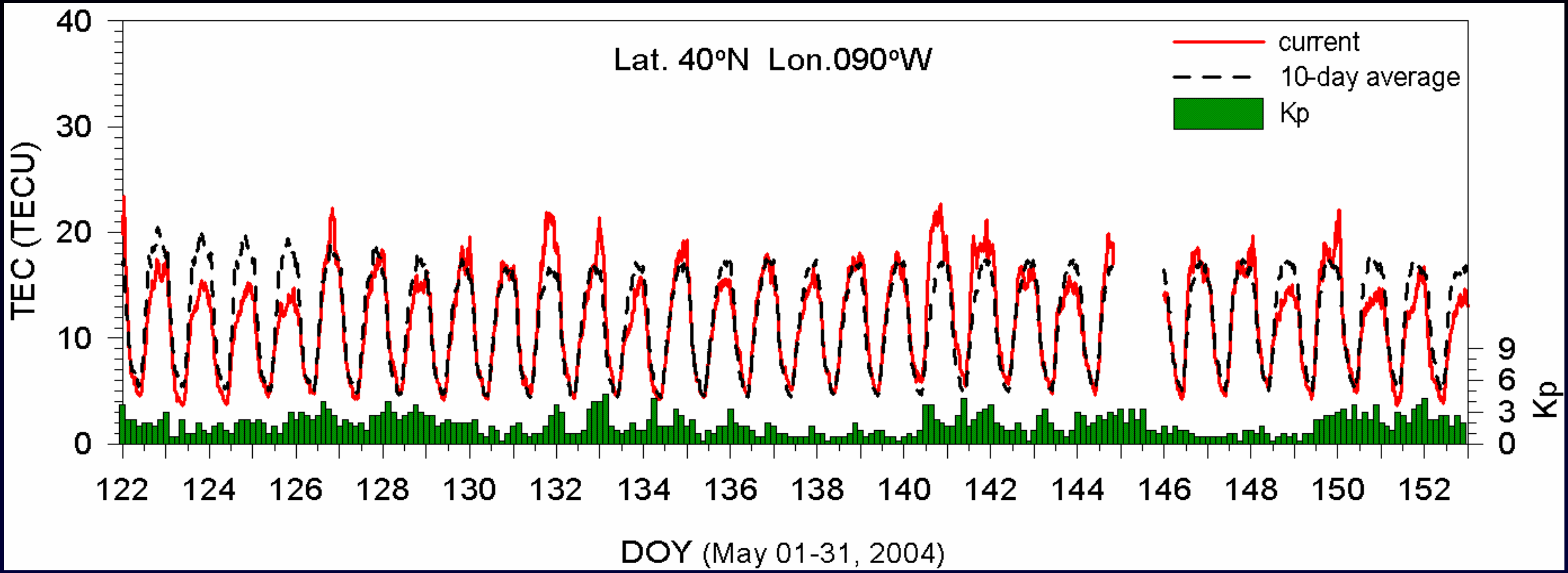
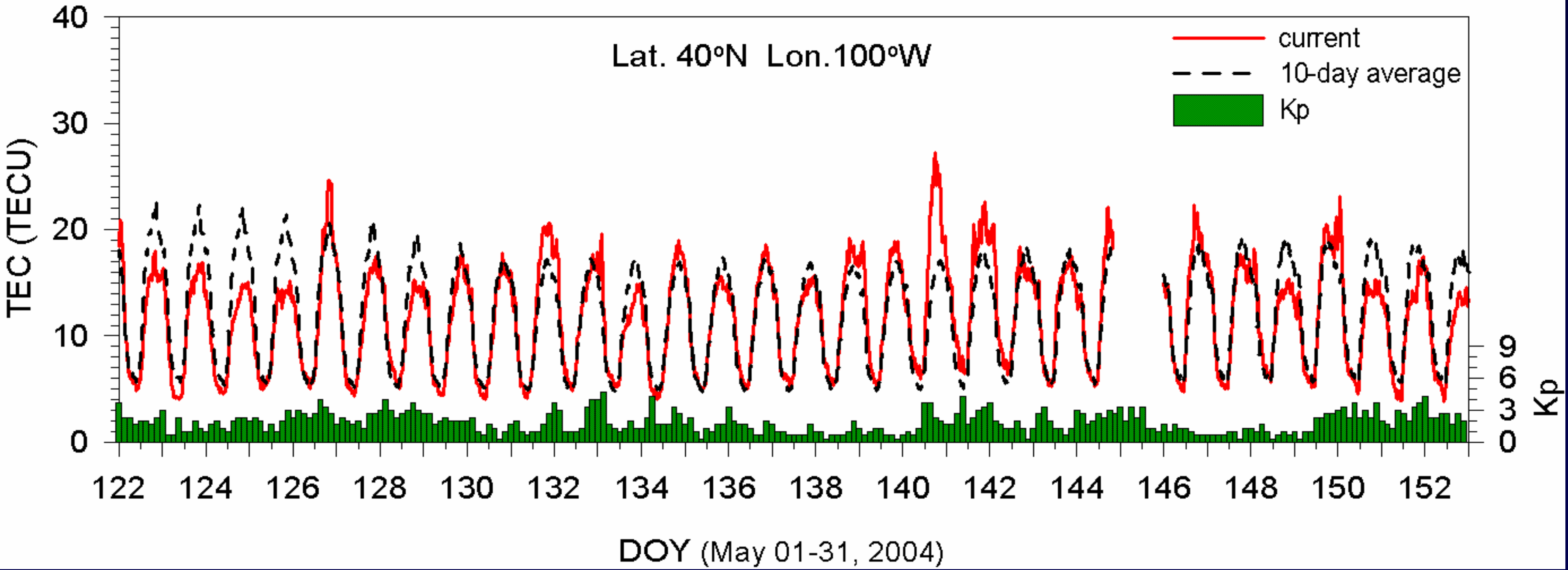
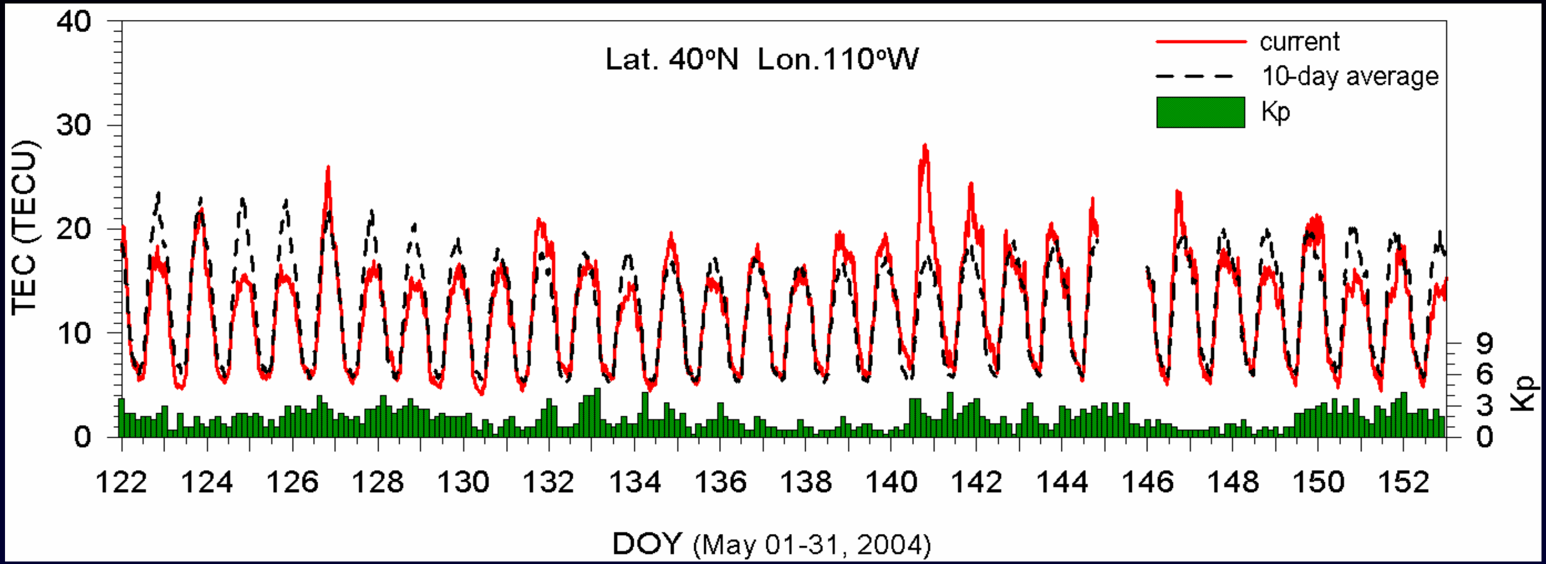
150
152
DOY (May 01-31, 2004)


current
10-day average
Lat. 40°N Lon.080°W
Vdrift (Jic-Piu)
average Vdrift (Jic-Piu)
TEC (TECU)
Vdrift (m/s)
DOY (May 01-31, 2004)

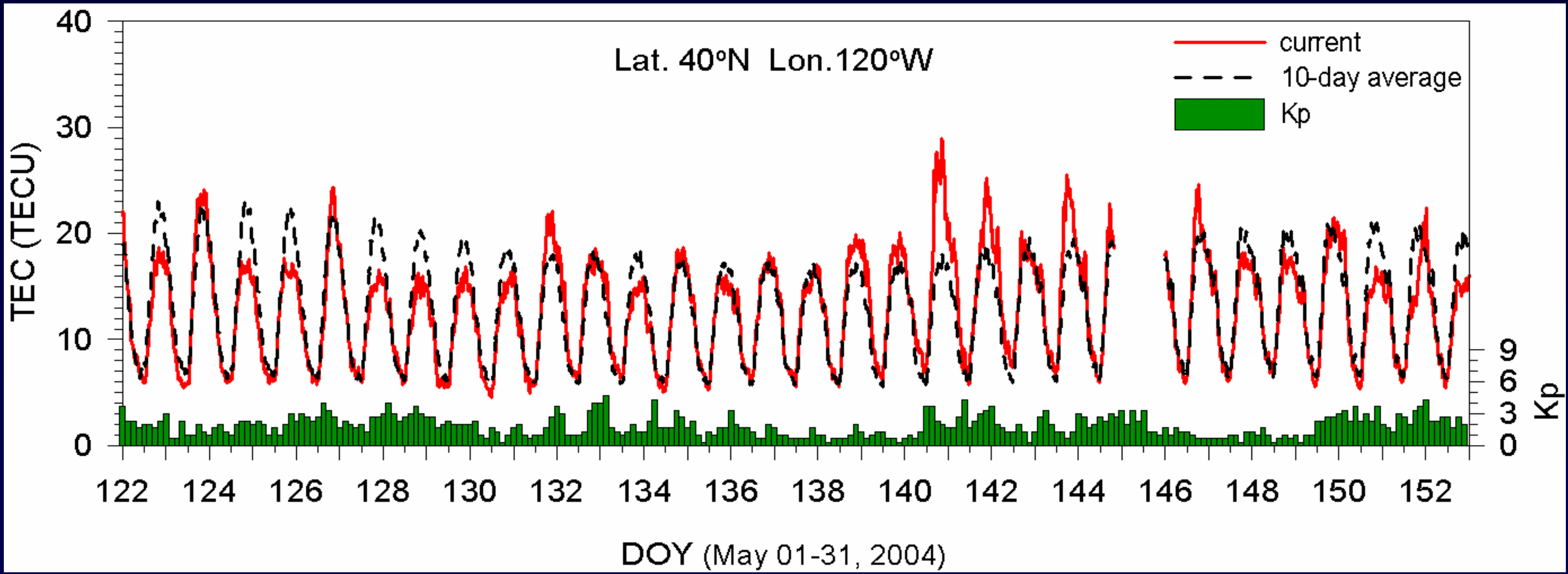

F10.7
E10.7
S1F10 (26-34 nm)
Lat. 40°N Lon.080°W
current
10-day average
TEC (TECU)
F10.7, E10.7, S1F10 (x10^{-22} W m^{-2} Hz^{-1})
DOY (May 01-31, 2004)


Lat. 40°N Lon.090°W
current
10-day average
Kp
TEC (TECU)
Kp
DOY (May 01-31, 2004)

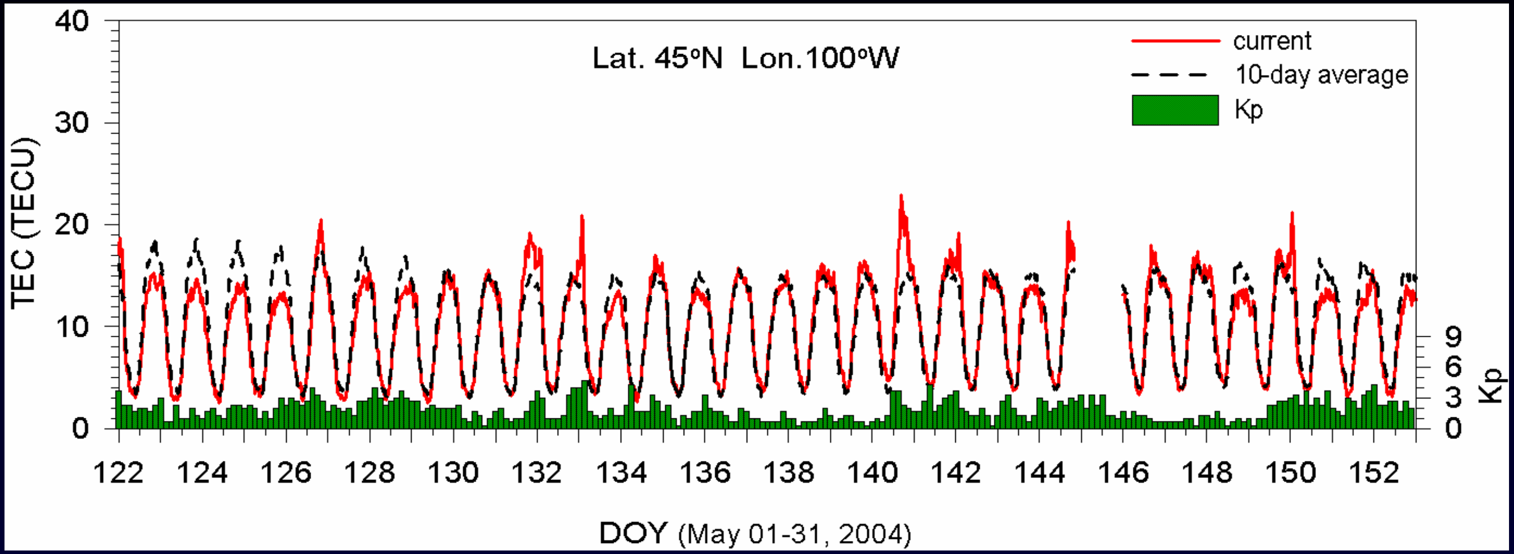

Lat. 40°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
Kp
DOY (May 01-31, 2004)

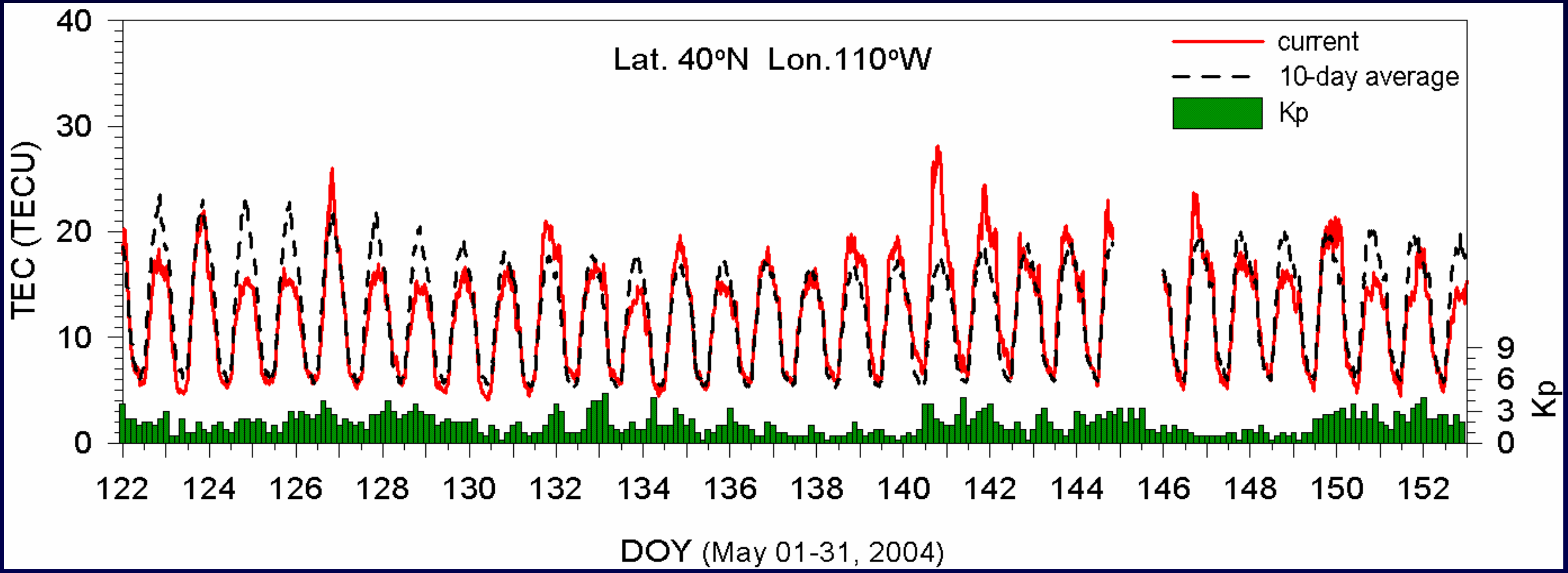


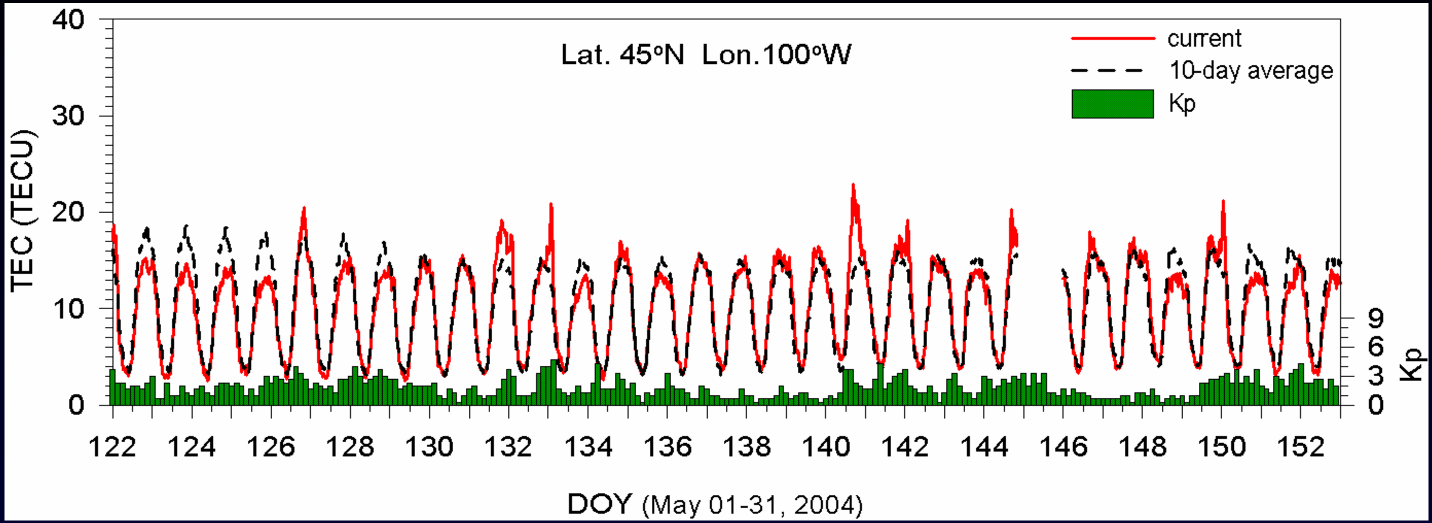
Lat. 40°N Lon.110°W
current
10-day average
Kp
TEC (TECU)
Kp
DOY (May 01-31, 2004)

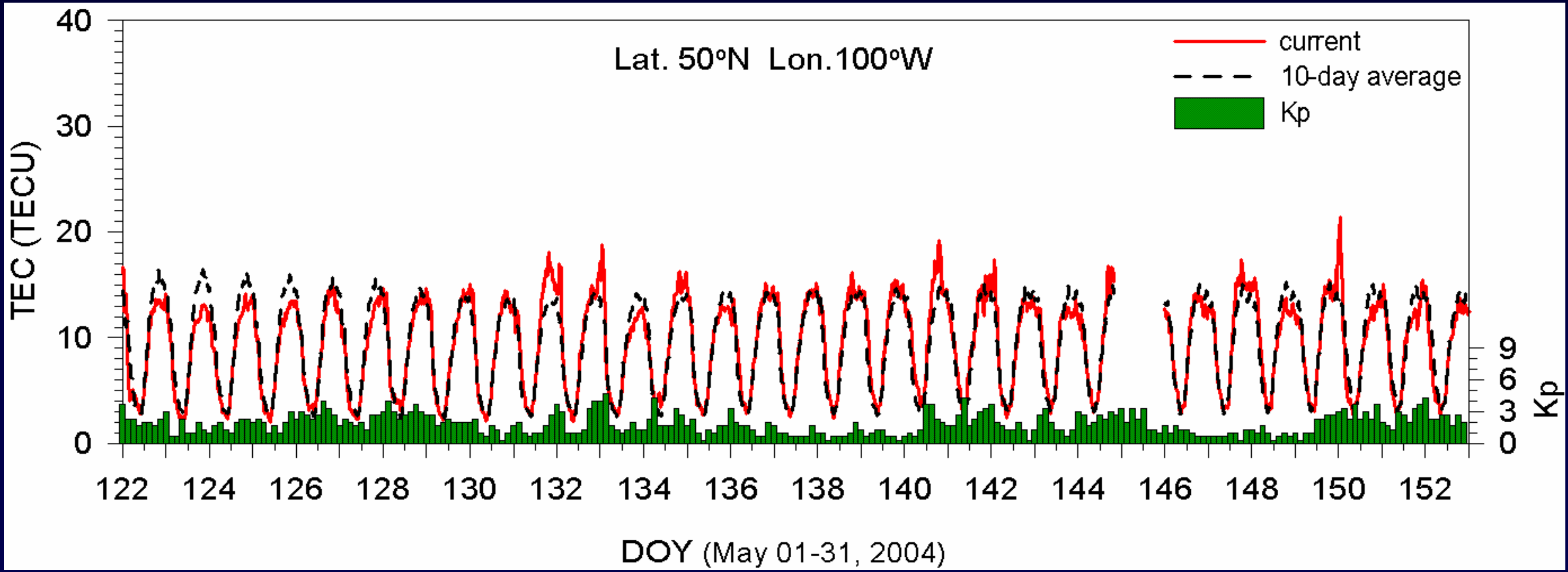


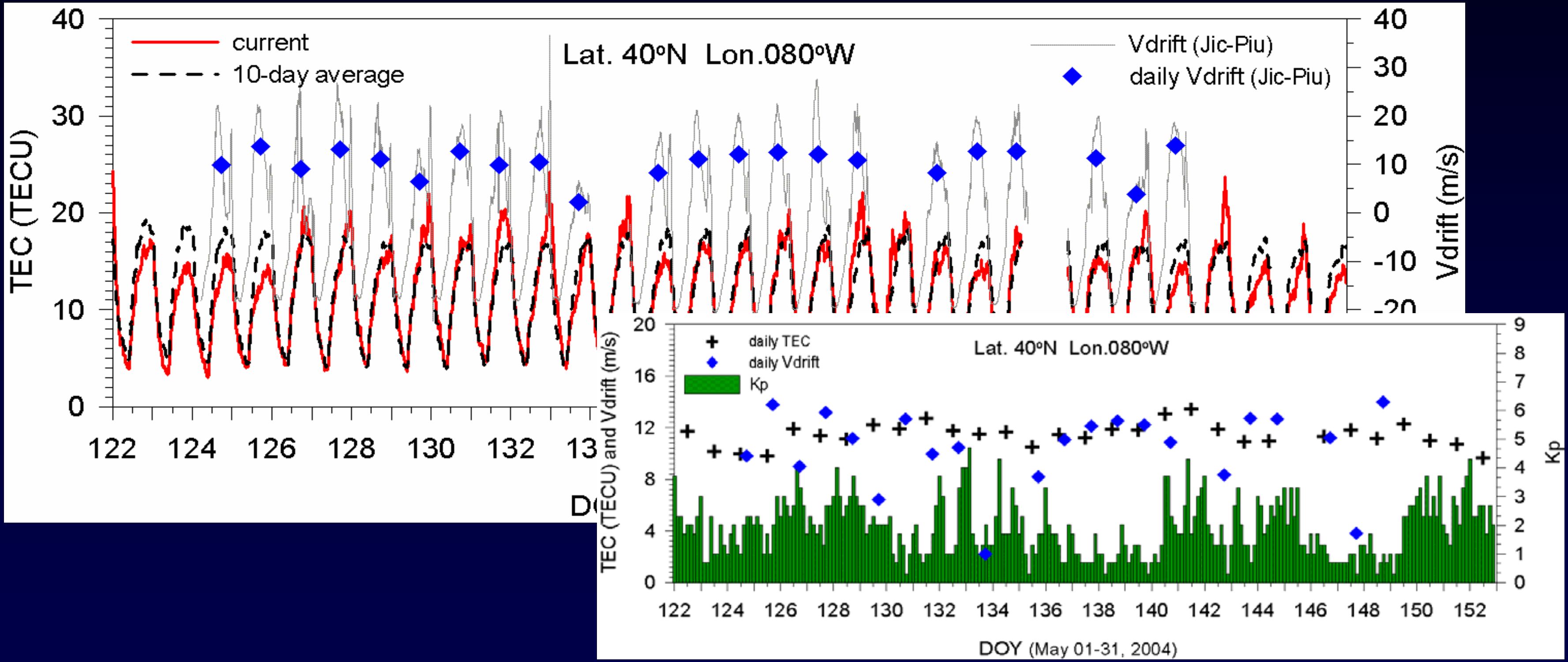
Lat. 40°N Lon.120°W
current
10-day average
Kp
TEC (TECU)
Kp
DOY (May 01-31, 2004)


Lat. 45°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
40
30
20
10
0
9
6
3
0
Kp
122
124
126
128
130
132
134
136
138
140
142
144
146
148
150
152
DOY (May 01-31, 2004)


Lat. 40°N Lon.110°W
current
10-day average
Kp
TEC (TECU)
40
30
20
10
0
9
6
3
0
Kp
122
124
126
128
130
132
134
136
138
140
142
144
146
148
150
152
DOY (May 01-31, 2004)


Lat. 45°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
40
30
20
10
0
9
6
3
0
Kp
122
124
126
128
130
132
134
136
138
140
142
144
146
148
150
152
DOY (May 01-31, 2004)


Lat. 50°N Lon.100°W
current
10-day average
Kp
TEC (TECU)
40
30
20
10
0
9
6
3
0
Kp
122
124
126
128
130
132
134
136
138
140
142
144
146
148
150
152
DOY (May 01-31, 2004)

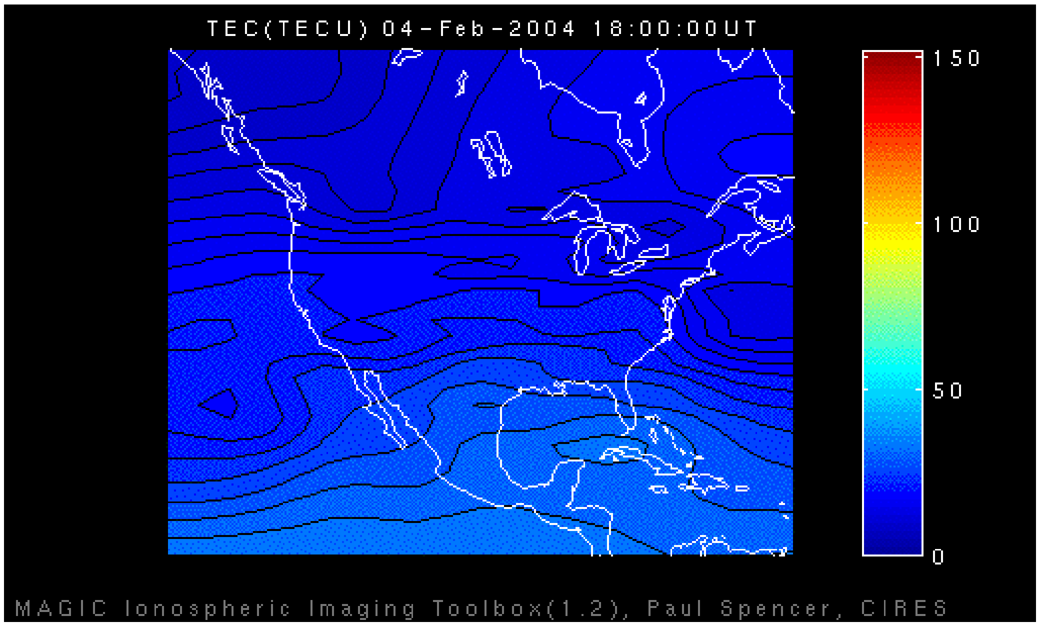


current
10-day average
Lat. 40ºN Lon.080ºW
Vdrift (Jic-Piu)
daily Vdrift (Jic-Piu)
TEC (TECU)
Vdrift (m/s)
daily TEC
daily Vdrift
Kp
Lat. 40ºN Lon.080ºW
TEC (TECU) and Vdrift (m/s)
Kp
DOY (May 01-31, 2004)

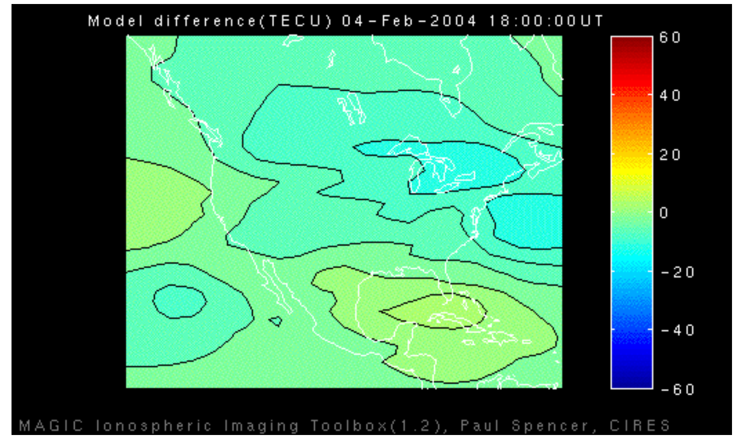
Real-time US-Total Electron Content Specification

Presented by the NOAA/Space Environment Center

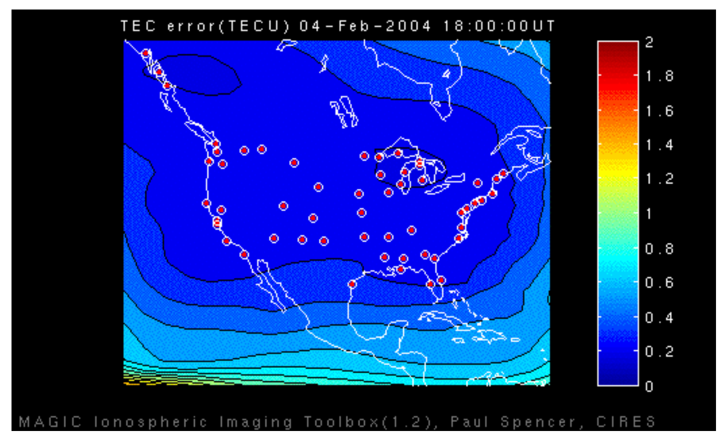
Latest Vertical TEC (2004 Feb 04 2100 UTC)



Latest TEC difference from average

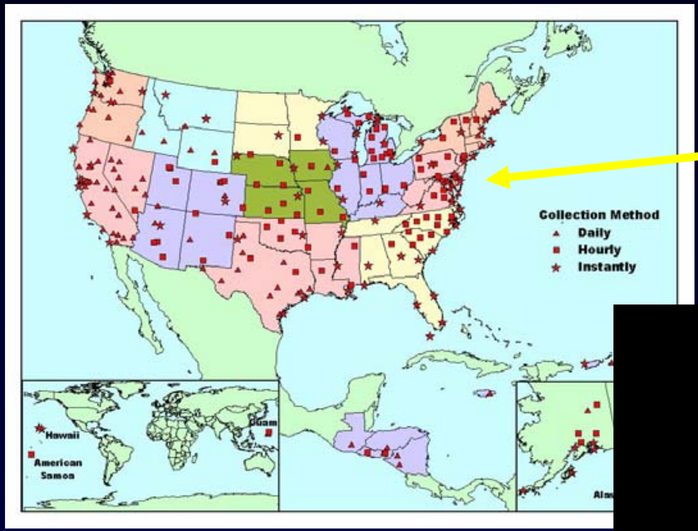


Latest TEC Kalman Standard Deviation



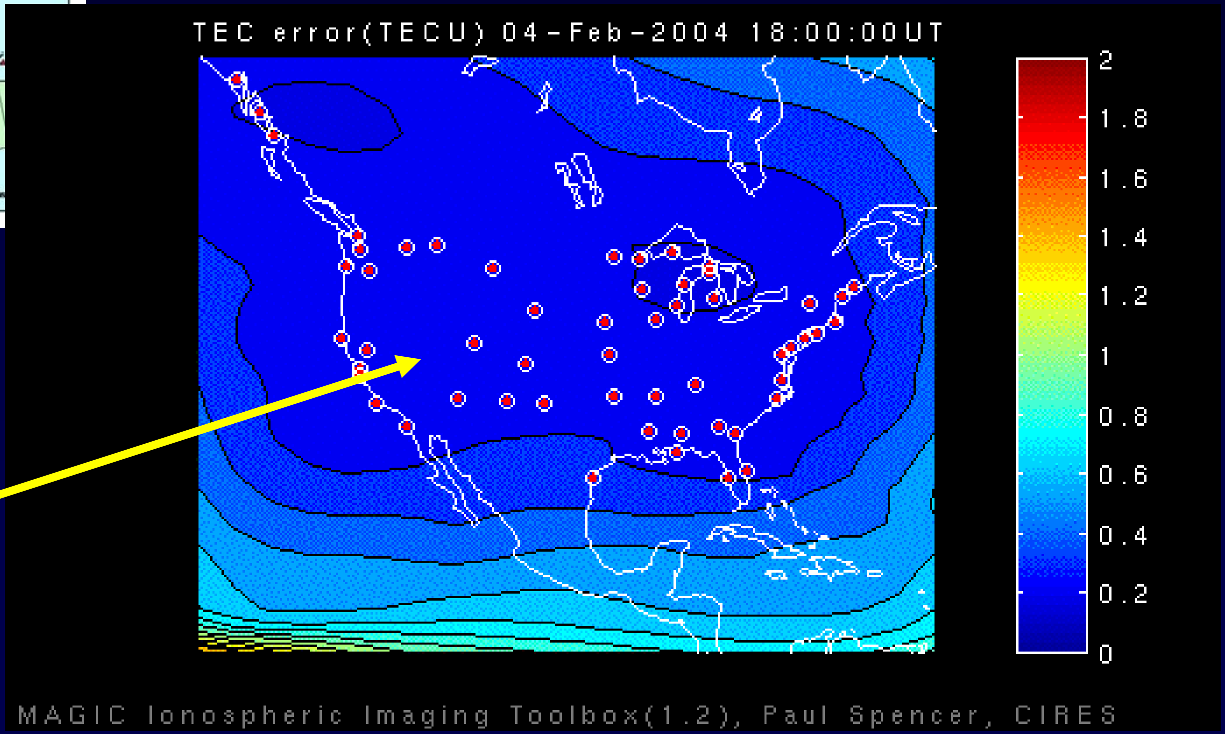
See internal web page:
http://www.sec.noaa.gov/ustec/index.html

Real-Time Stations



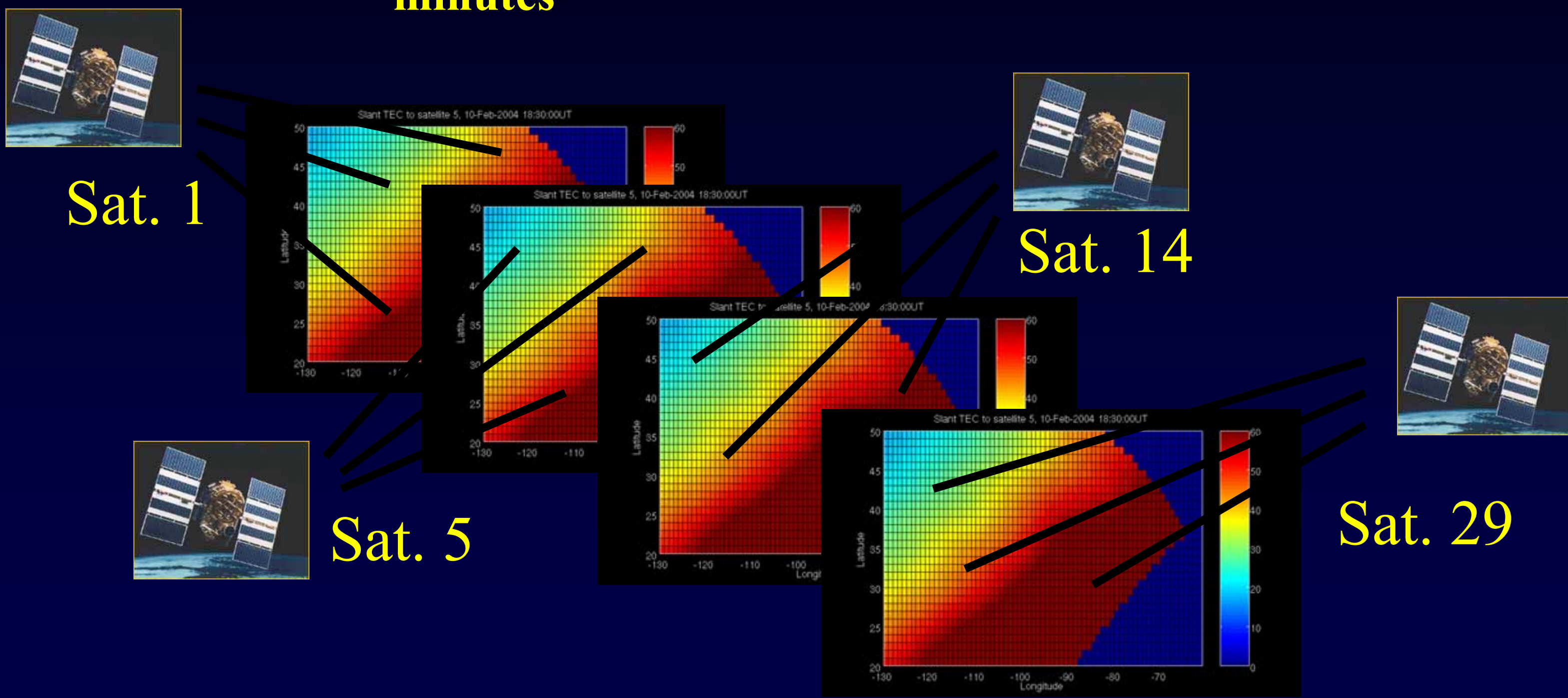
Data from ~400 CORS (Continuously Operating Reference Stations) GPS dual-frequency receivers are collected by NGS (National Geodetic Survey)

Over 100 stations are available in real-time: including data from US Coast Guard and WAAS sites



Slant-Path TEC Maps

2-D maps of of slant path TEC over the CONUS for each GPS satellite in view updated every 15 minutes



....etc

Applications:

1. Ionospheric correction for single frequency GPS positioning
2. Dual-frequency integer ambiguity resolution for rapid centimeter accuracy positioning

Products

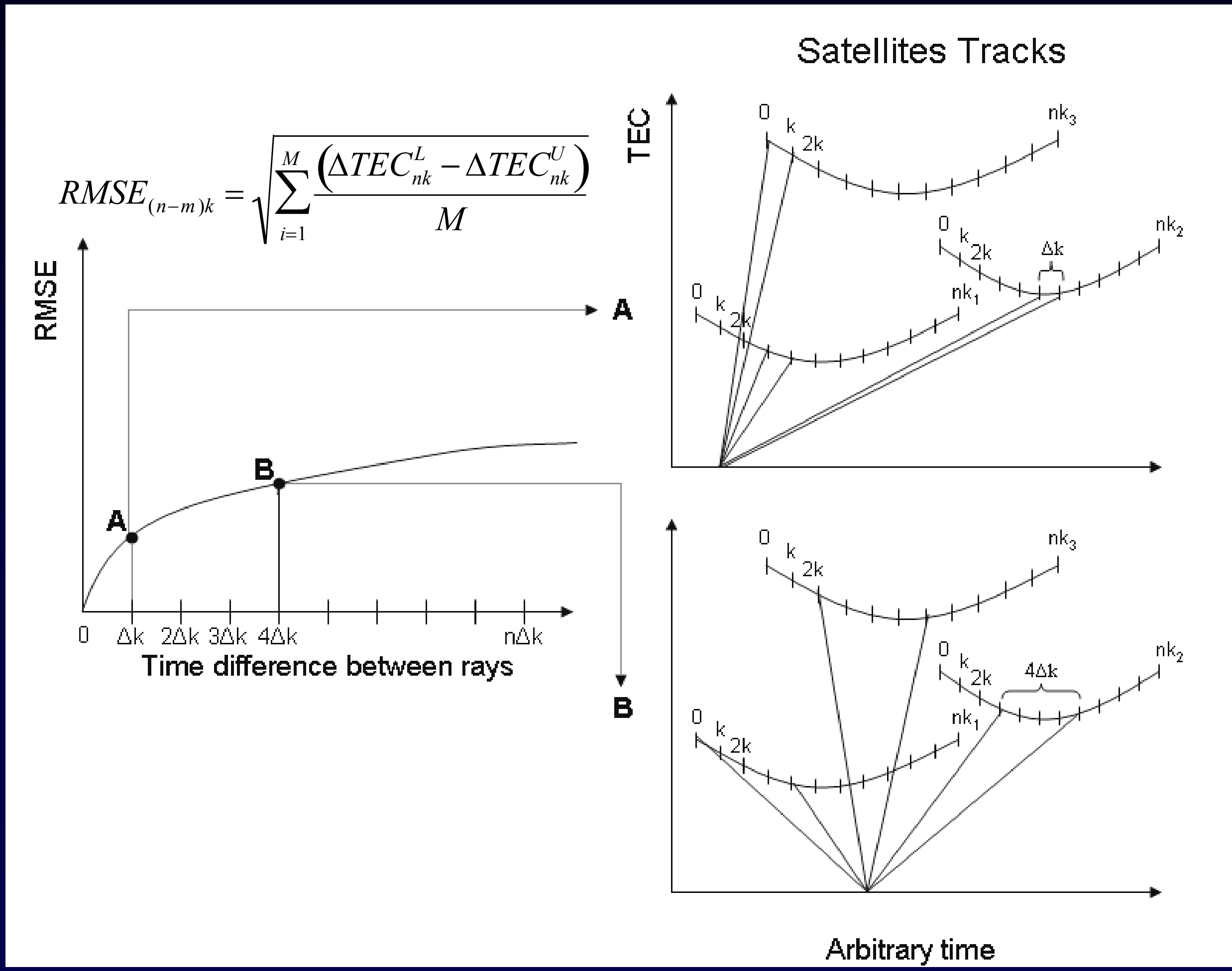
- Vertical TEC map over CONUS updated every 15 minutes
- Map of Kalman standard deviation as estimate of uncertainty of TEC, and current data sites
- Map of difference from average

- Data files:
    a) vertical TEC
    b) slant path TEC for each GPS satellite in view

- Vertical TEC and slant path 2 days in arrears

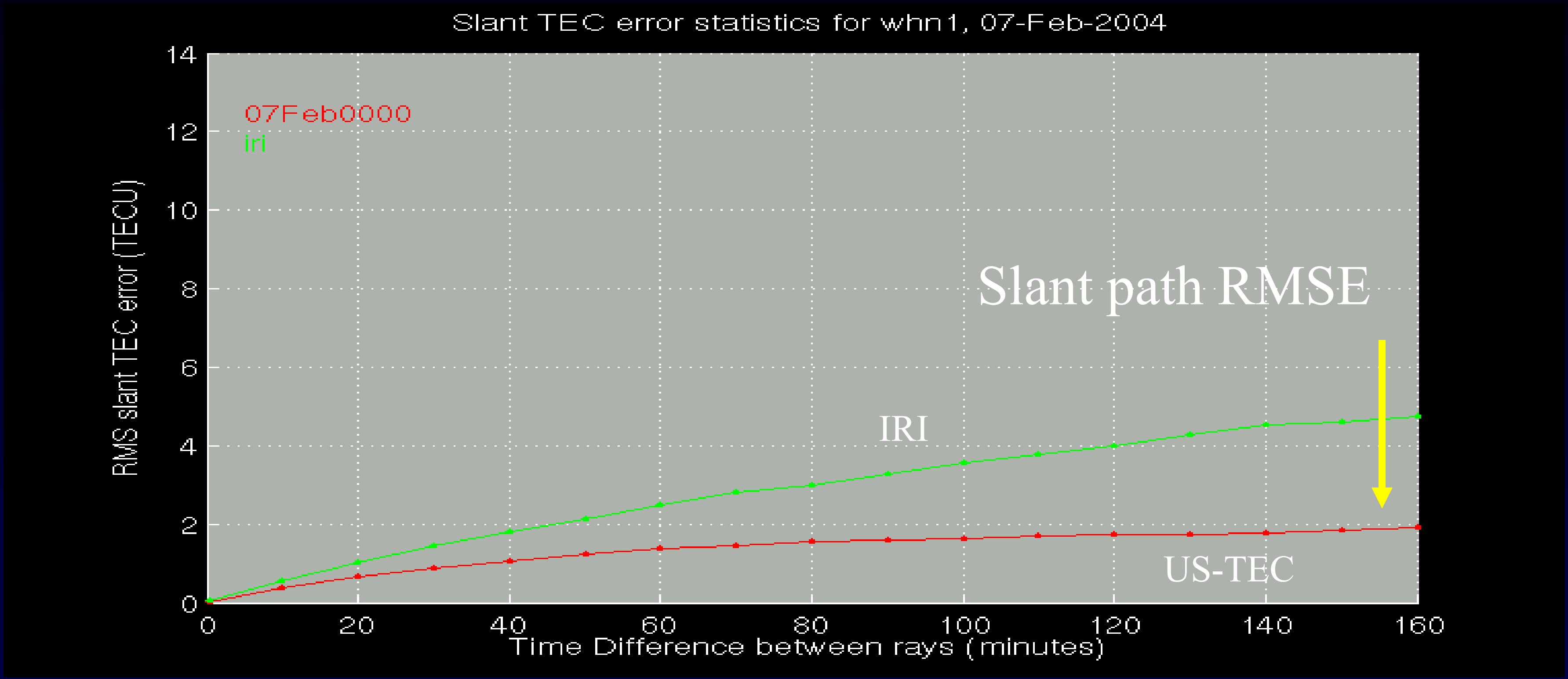
Differential Validation

- Integrate through US-TEC model at two different times.
- Compare directly to the phase difference in the original RINEX data file.
- As time separation increases, errors in US-TEC map become uncorrelated and approach true uncertainty.



Araujo-Pradere et al. 2006

US-TEC "Differential" Validation

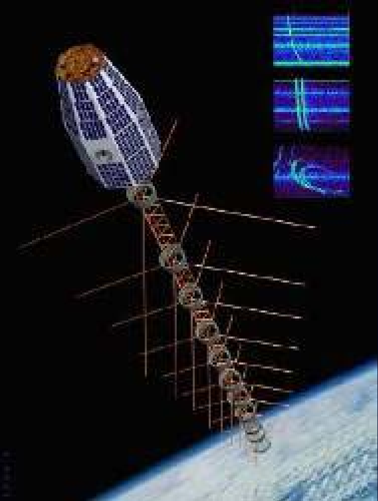


- 9 GPS station on regular grid over CONUS
- Validation stations not included in assimilation process
- Build up statistics every 5th day over 6 months
- Daily average RMSE for each site

Validation Statistics: “differential” TEC

	Jul						Aug						Sep						
IRI	5	10	15	20	25	30	5	10	15	20	25	30	5	10	15	20	25	30	AVE
pabh	2.6	4.1	4.4	3.2	6.1	1.6	2.6	2.0	4.5	3.9	4.0	2.8		4.2	2.1	2.0	3.0	2.9	3.4
ybhb	3.4	4.5	4.6	4.0	7.3	2.8	2.9	3.8	4.5	4.5	3.9	4.2		4.4	3.3	3.0	4.1	4.1	4.0
bill	5.0	5.0	5.4	5.2	7.8	3.3	4.0	5.2	4.5	4.0	4.2	4.6		3.5	3.8	9.7	4.9	6.4	5.1
clk1	2.3	2.4	5.5	4.3	6.9	2.6	3.0	2.9	4.1	3.9	4.2	4.5		5.0	4.7	2.1	2.5	3.1	3.8
hbrk	3.7	3.6	6.0	4.7	9.5	3.5	3.6	3.1	5.3	3.4	3.2	3.5		4.7	4.9	2.8	4.0	3.4	4.4
arp3	4.9	5.1	5.1	5.3	8.1	3.3	3.6	4.6	4.9	4.1	3.2	6.9		4.2	4.7	3.7	5.7	5.0	5.0
wes2	2.9	4.0	4.9	5.0	6.7	3.0	3.0	3.4	5.8	3.7	2.9	4.8		4.8	4.2	2.7	2.3	2.5	3.8
vims	3.5	4.9	5.8	4.8	8.6	4.0	2.9	3.5	6.0	2.6	3.3	4.7		3.1	5.3	2.8	3.6	2.9	4.3
ccv3		5.9	6.2	5.1	7.6	3.6	3.2	3.2	6.3	3.4		4.3		3.1	4.3	2.8	4.2	3.1	4.5
AVE	3.5	4.4	5.3	4.6	7.6	3.1	3.2	3.5	5.1	3.7	3.6	4.5		4.1	4.2	3.5	3.8	3.7	4.2
USTEC																			
pabh	1.9	1.9	1.8	1.6	3.2	1.1	1.6	1.2	2.0	2.0	1.9	1.8		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.9
ybhb	2.0	2.8	2.3	2.1	2.9	1.7	1.9	1.6	2.5	2.6	2.5	2.3		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.3
bill	3.1	3.5	3.4	3.5	3.7	2.1	2.5	2.4	3.0	2.8	2.3	2.9		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.2
clk1	1.6	1.5	2.1	2.5	3.2	1.3	1.6	1.9	1.8	2.1	2.4	2.9		2.2	2.4	1.2	1.3	1.5	1.9
hbrk	1.9	1.6	2.2	2.6	3.9	1.5	1.7	1.7	2.1	2.1	2.3	2.0		2.0	2.3	1.3	1.6	1.9	2.1
arp3	3.4	2.8	2.8	3.9	2.8	1.9	2.7	2.6	3.0	3.5	1.8	4.7		3.3	3.3	2.3	[illegible]	3.3	3.2
wes2	1.7	1.9	2.2	1.8	2.9	1.4	1.6	1.9	2.6	1.3	1.8	2.4		2.3	2.3	1.5	1.4	1.6	2.0
vims	1.9	1.7	2.1	2.0	4.0	1.5	1.8	1.9	2.4	1.6	2.3	2.3		2.0	2.5	1.7	1.5	1.4	2.0
ccv3		2.8	2.4	3.0	3.1	1.6	2.0	2.2	2.8	2.4		2.4		2.4	2.6	2.1	2.3	2.3	2.7
AVE	2.2	2.3	2.4	2.5	3.3	1.6	1.9	1.9	2.5	2.3	2.2	2.6		2.3	2.4	2.5	2.0	2.2	2.4
USTEC - IRI																			
pabh	-0.8	-2.2	-2.5	-1.5	-2.9	-0.4	-1.1	-0.8	-2.5	-1.9	-2.1	-1.0		-2.5	-0.8	-0.4	-1.3	-1.2	-1.5
ybhb	-1.4	-1.7	-2.4	-1.9	-4.4	-1.1	-1.0	-2.2	-2.0	-1.9	-1.3	-1.9		-2.1	-1.3	-1.2	-2.0	-1.6	-1.7
bill	-1.9	-1.6	-2.0	-1.7	-4.0	-1.2	-1.5	-2.8	-1.5	-1.2	-1.9	-1.7		-0.9	-1.2	-0.8	-2.3	-3.0	-1.9
clk1	-0.7	-0.9	-3.4	-1.8	-3.7	-1.3	-1.4	-1.0	-2.4	-1.8	-1.8	-1.5		-2.8	-2.3	-0.9	-1.2	-1.7	-1.9
hbrk	-1.9	-2.0	-3.8	-2.1	-5.6	-2.0	-1.9	-1.3	-3.2	-1.4	-0.8	-1.5		-2.7	-2.6	-1.5	-2.4	-1.5	-2.3
arp3	-1.5	-2.3	-2.3	-1.5	-5.3	-1.4	-1.0	-2.0	-1.8	-0.6	-1.4	-2.2		-1.0	-1.4	-1.4	-2.8	-1.7	-1.8
wes2	-1.2	-2.1	-2.7	-3.2	-3.7	-1.6	-1.4	-1.5	-3.2	-2.3	-1.0	-2.3		-2.6	-1.9	-1.1	-0.9	-1.0	-1.9
vims	-1.6	-3.3	-3.7	-2.8	-4.5	-2.5	-1.1	-1.6	-3.6	-1.1	-1.0	-2.4		-1.2	-2.8	-1.1	-2.1	-1.5	-2.2
ccv3		-3.0	-3.8	-2.1	-4.5	-2.0	-1.2	-0.9	-3.5	-1.0		-1.9		-0.7	-1.7	-0.7	-1.8	-0.8	-1.8
AVE DIF	-1.4	-2.1	-3.0	-2.1	-4.3	-1.5	-1.3	-1.6	-2.6	-1.4	-1.4	-1.8		-1.8	-1.8	-1.0	-1.9	-1.5	-1.9
ap index	7	8	9	9	122	7	7	14	7	14	7	34	7	5	14	13	5	4	
# stations	58	59	59	58	58	57	58	57	57	53	49	58	3	58	59	58	57	57	50

2.4 TEC units

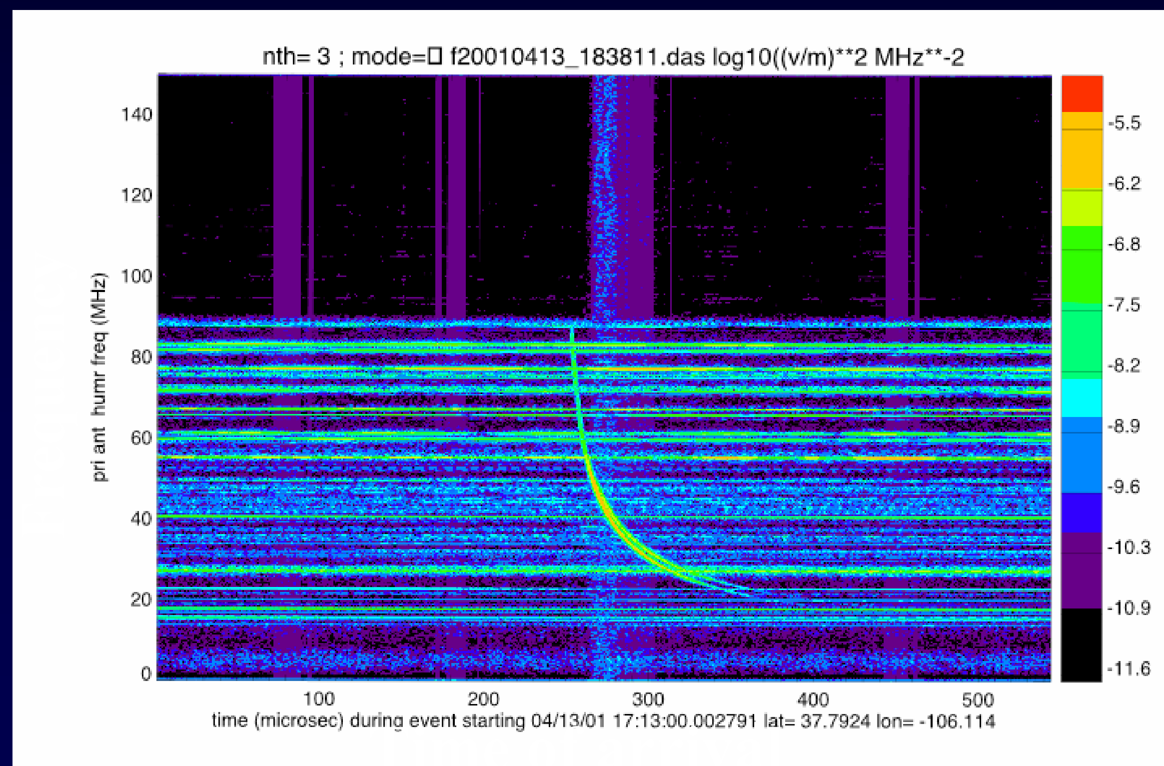


Absolute validation: FORTE

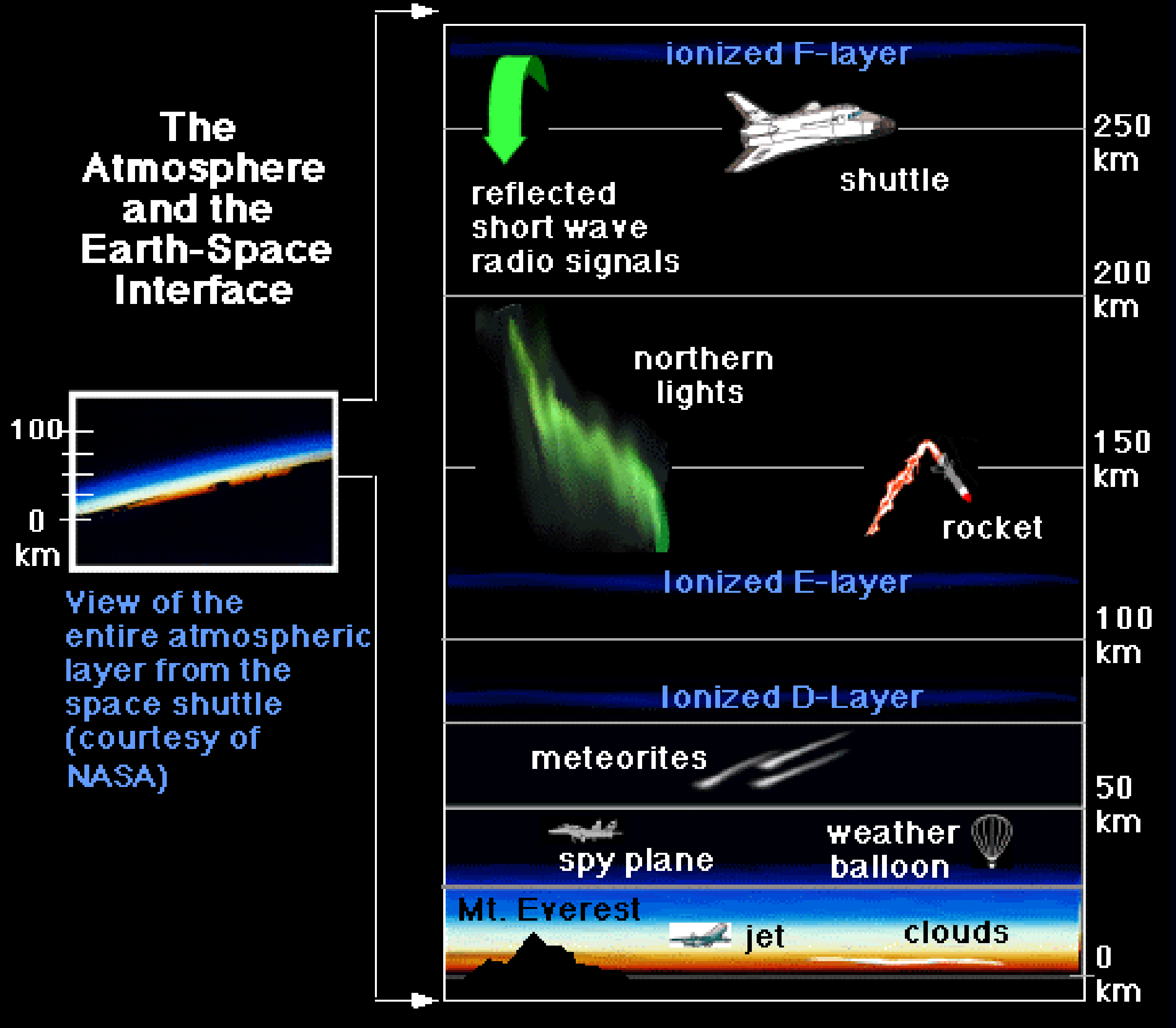
Fast Onboard Recording of Transient Events satellite
(Los Alamos, Abe Jacobson)

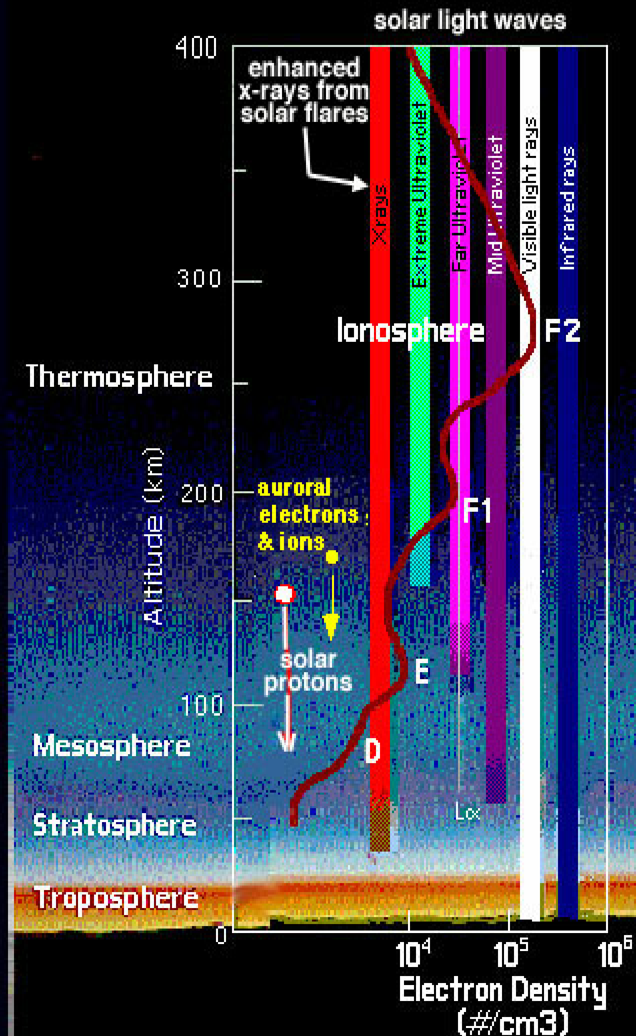
- Phase or arrival time as function of frequency
- Separate O and X traces
- Fit to k/f^2 dependence provides TEC estimate

- Broad-band RF receiver 30-300 MHz at 800 km altitude
- Designed to monitor lightning
- Pulse transmitted from Los Alamos (simulated lightning)
- Possible to estimate line-of-sight TEC between transmitter and FORTE satellite
- Broad-band signal/receiver eliminates phase ambiguity so produces an "absolute" TEC estimate (uncertainty estimate is about 1 to 2 TEC units)
- Issues are
  - bending of the rays,
  - plasmaspheric content, and having to sub-sample US-TEC vertical domain



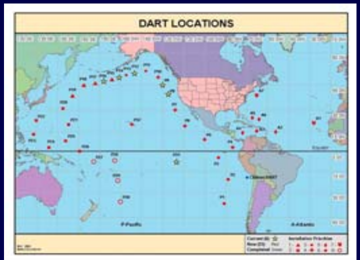
The Thermosphere and Ionosphere





Future Plans for US-TEC

- Increase number of stations over CONUS to ~120 (including NOAA-FSL and FAA-WAAS stations)
- Include Canadian stations to improve TEC on poleward side and provide values over North America
- Increase cadence to 5 minutes
- Provide short-term forecast (10 to 30 minutes) to bring beyond, real-time
- Need sites to the south (Mexico and Caribbean)
- Buoys over oceans



Questions to: Tim Fuller-Rowell
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tim.fuller-rowell@noaa.gov
303-497-5764